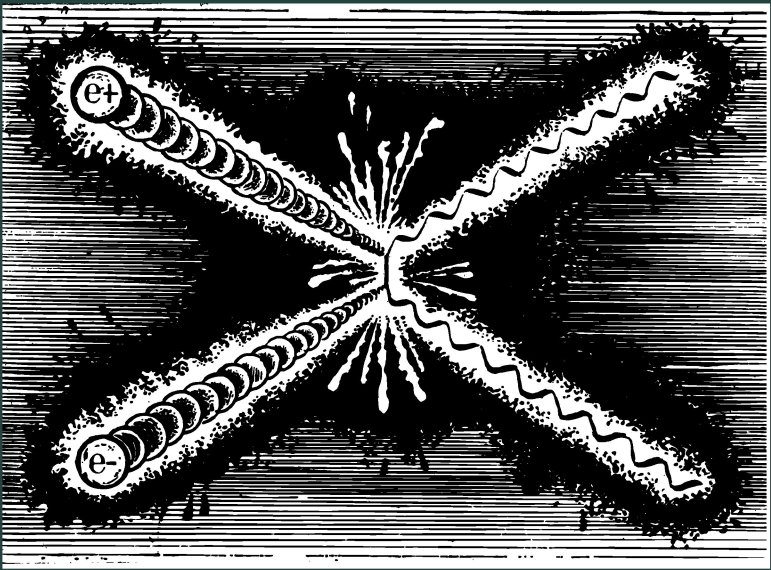
PHYSICS OF THE MICROWORLD

Mir Publishers

Moscow



K. I. Shcholkin

ИЗДАТЕЛЬСТВО • МИР •

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ФИЗИКА МИКРОМИРА

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Physics of the Microworld

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Hydrogen Atom. Quantum Numbers

The hydrogen atom consists of a positively charged nucleus (proton) and an electron rotating about it. The electron has a charge equal in value but opposite in sign to that of the proton. As a whole, the hydrogen atom is electrically neutral. Two oppositely charged particles are attracted to each other by an electrostatic force. Therefore the electron does not fly away from the nucleus but rotates about it just as the earth rotates about the sun, being attracted to it by the force of gravitation.

The proton is 1836 electron masses (em). Thus, the mass of the hydrogen atom is practically equal to that of the proton. One gram of atomic hydrogen contains 6.02×10^{23} atoms, hence the mass of the hydrogen atom is $1/(6.02 \times 10^{23}) = 1.67 \times 10^{-24}$ g. If we put together all the water contained in the seas and oceans of our planet, its mass will be approximately as many grams as there are atoms in one gram of hydrogen. The mass of the electron, which is 1/1836 of the total mass of the hydrogen atom, equals 9.1×10^{-28} g.

The diameter of the hydrogen atom cannot be measured precisely because the atom has no clearly defined boundary. Its approximate diameter is 10^{-8} cm, that is a hundred-millionth fraction of a centimetre. This unit is termed the angstrom after the Swedish scientist who introduced it about one hundred years ago for measuring wavelengths in light spectra.

According to the Bohr theory, which has now been supplanted by quantum mechanics, the electron orbit in the hydrogen atom has a radius of 0.52917 angstrom (Å). Consequently, the diameter of the hydrogen atom is about 1.06 Å. But this figure gives

only a very approximate idea of the size of the hydrogen atom.

The radius of the hydrogen nucleus (proton) is around one hundred thousand times less than that of the hydrogen atom and equals 1.3×10^{-13} cm, or 1.3 fermis. The radius of the proton is approximately as many times less than one centimetre as there are centimetres in the distance from earth to sun. The nuclear unit of length, the *fermi* (1 fermi $= 10^{-13}$ cm), is named after the great Italian physicist Enrico Fermi, who died in the prime of his talent.

The density of matter in the proton is phantastic, about 2×10^{14} g/cm^3, or two hundred million metric tons per cubic centimetre. This is of the order of the density of matter in all atomic nuclei, e.g. of oxygen, iron, uranium. If we could pack tightly together the nuclei of steel produced by all works in the world during a whole year, they would occupy a volume only slightly exceeding one cubic centimetre. A five-year world output of steel could then be squeezed into a dessert-spoon.

Electrons rotate about the nucleus only in definite orbits which are spaced at different distances from the nucleus and form the electron shells of the atom. The shells are denoted by the letters K, L, M, N, O, P, etc., in the order of increasing distance from the nucleus. An electron moving in the innermost orbit is called a K-electron, and so on. The shells can be given numbers: 1 (K-shell) 2, 3, 4 and so on. These are called *principal quantum numbers of the atom* ($n=1$, $n=2$, etc.).

In its normal state, the electron in the hydrogen atom is in the first shell. To shift an electron from one of the innermost shells, or orbits, to a more distant one, it must be imparted a definite amount (a quantum) of energy. On returning to the original orbit,

closer to the nucleus, the electron gives off the same amount of energy in the form of a light quantum. All states of the hydrogen atom which have a principal quantum number exceeding unity are called *excited states*. The radius of an atom in an excited state is proportional to the square of the principal quantum number. The diameter of an atom with a principal quantum number equal to two is four times as great as the diameter of an unexcited atom. With $n=3$ the diameter is nine times as great, with $n=10$, one hundred times, and so on.

The motion of electrons in strictly defined orbits, the absorption and emission of definite portions of energy, all these properties are inherent only in the microworld. Nothing of the kind is observed in the world of large bodies, the macroworld.

The quanta emitted and absorbed by an atom during electron transition have an interesting feature: they are proportional to the oscillation frequency ν of the light emitted or absorbed. The frequency ν can only be an integer. The magnitude of the quantum is equal to

$$E=h\nu \tag{1}$$

Here, h is a constant which is often encountered in physics of the microworld. This is the Planck constant, which was introduced in 1900 by the German physicist Max Planck, the founder of quantum mechanics. This unit is sometimes called the *quantum of action*, it is equal to 6.626×10^{-27} erg. s. Its dimensionality is the same as that of the product of energy by time, or of the angular momentum. Recall that the unit of energy, the erg, is the work done by a force of one dyne over a path of one centimetre. The dyne is a force which increases each second the velocity of a body with a mass of one gram by one centimetre per second (CGS system).

The reader should be warned here that he will have to overcome a few boring pages. But if he makes an effort and familiarizes himself with the orbital angular momentum and the spin and also realizes that they can have only definite values (are quantized), it will be easier for him to understand the rest of the book. If he manages to grasp the meaning of all quantum numbers as well, he will then have no trouble at all.

The angular momentum is equal to the product of the mass of a rotating body by its velocity and by the distance from the centre of gravity of the body to the point about which it is rotating. The angular

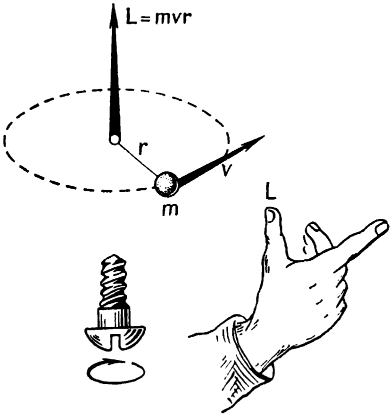

Fig. 1. The angular momentum L is equal to the product of the momentum mv (m—mass, v—velocity) by the distance r from the centre of gravity of the rotating mass to the rotation centre. The angular momentum is directed as a right-handed screw turning with the mass. If you point your index finger along the motion of the body and the middle finger towards the rotation centre and hold the thumb perpendicular to both, it will show the direction of the angular momentum.

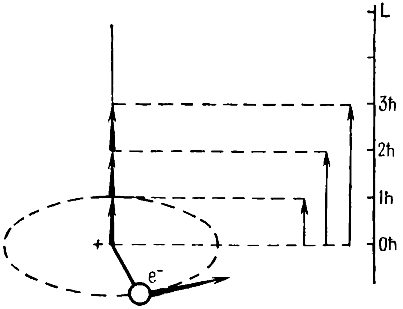

Fig. 2. Projection of the orbital angular momentum of an electron. It can only have values multiple of $\hbar$ ($0\hbar$, $1\hbar$, $2\hbar$, etc.).

momentum is a vector directed along rotation axis as a right-handed screw advances turning together with the body.

The Planck constant is a very small magnitude for the macroworld, but it is quite usual for the world of microscopic bodies. For instance, the angular momentum of an electron rotating about the nucleus (more precisely, the projection of the momentum onto an arbitrary direction) is equal to a whole number multiplied by the ratio of the Planck constant to 2π. This ratio, which is denoted as $\hbar = h/2\pi$, is also called the quantum of action and is equal to 1.05×10^{-27} erg. s. The actual angular momentum is usually unknown since it cannot be measured.

Experiment and quantum-mechanical theory show that the projection of the angular momentum of an electron is quantized, i.e. it can have only definite values. For an electron rotating in one and the same orbit it may assume several different values each of which differs from the neighbouring one by $\hbar$. This

magnitude is equal to the so-called orbital quantum number *(l)* multiplied by $\hbar$. The maximum orbital quantum number for a particular shell (*K*, *L*, *M*, etc.) is less by unity than the principal quantum number, while the minimum is zero. Thus, for the *K*-shell the principal quantum number $n=1$, and the orbital quantum number can have only one value, $l=0$. For the *L*-shell, the principal quantum number $n=2$, and the maximum orbital quantum number $l=1$. But this shell can also have an orbital quantum number less by unity, i.e. zero. For the *M*-shell $n=3$, and the possible orbital quantum numbers are $l=2$, $l=1$, $l=0$. In a similar way one can find the orbital quantum numbers for other shells. The higher the principal quantum number, the wider is the range of orbital quantum numbers.

The states corresponding to the values $l=0$, 1, 2, 3, etc. are denoted by the letters *s*, *p*, *d*, *f*, etc., respectively. The principal quantum numbers characterize the electron energies, which depend on the distance from the electron to the nucleus. The orbital quantum numbers express the possible values of the projection of the angular momentum of the electron. Knowing the orbital quantum number one can find the square of the angular momentum of the electron:

$$M^2=l(l+1)^2$$

In the next section we will revert to quantum numbers. Now we will restrict ourselves to a few remarks. In the *K*-shell, the first shell from the nucleus, the orbital quantum number is zero, and thus the angular momentum of the electron is also zero; only the *s*-state is possible here. But if the electron *rotates* in an orbit, it *must have* an angular momentum! This is an obvious contradiction. Hence, our knowledge is insufficient at present. In fact one cannot speak of rotation

of an electron about the nucleus when it is in the s-state. It is more correct to say that there is an equal probability of the electron being at any point of the surface of the sphere which surrounds the nucleus and has a radius corresponding to the principal quantum number.

When the angular momentum of an electron is non-zero, the electron rotates with a certain velocity in a more or less definite orbit. Therefore its properties differ somewhat from those of an electron in the same shell but with no orbital angular momentum. This is why a shell with a principal quantum number above unity has several subshells, which differ in orbital quantum numbers. For the first shell, the orbital momentum is zero and this shell is not subdivided into subshells according to orbital numbers. The second shell has two subshells, s and p ($l=0$ and $l=1$), while the third shell has three subshells, s, p and d ($l=0$, 1 and 2).

Besides the principal and orbital quantum numbers there are two more quantum numbers, which increase the number of the possible states of an electron in the hydrogen atom. An electron, moving in an orbit, sets up an electric current. It is known that an electric current in an annular conductor induces a magnetic field. Therefore an electron rotating in its orbit forms a sort of a straight magnet positioned along the axis of rotation. Here, the magnitude of the magnetic field is characterized by magnetic moment. But we will revert to this subject later on. If a magnet formed by an orbital current is placed in an external magnetic field, it will be inclined at a certain angle to the direction of the external field. The smaller the angle of inclination, the longer the projection of the magnetic moment of the orbital current onto the direction of the external field.

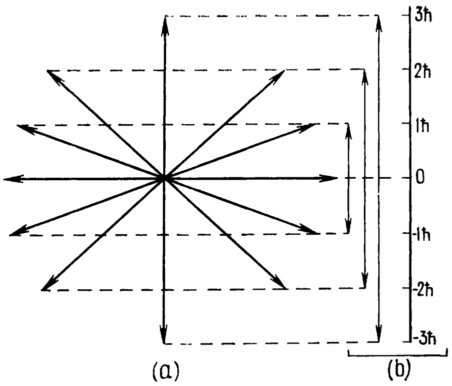

Fig. 3. Possible orientations of the orbital angular momentum of an electron (orbital quantum number 3) in an external magnetic field (*a*). The value of the projection of the orbital momentum onto the direction of the external magnetic field (*b*). The magnetic quantum number assumes values 3, 2, 1, 0, —1, —2, —3.

It appears that the projection of an orbital momentum onto the direction of an external magnetic field is also quantized, it can only assume values differing by a whole number of $\hbar$'s. Hence, if the orbital quantum number is 2, the *magnetic quantum number m* (the number determining, in terms of $\hbar$, the value of the projection of the orbital momentum onto a given direction) may be 2, 1, 0, —1, or —2. For an orbital quantum number equal to l the magnetic quantum number may assume any value from l to $-l$, the adjacent values differing by unity. In a magnetic field the sublevel corresponding to the orbital number l splits up into $(2l+1)$ states differing in magnetic quantum numbers. When an atom is in a magnetic field, electrons in states with different magnetic quan-

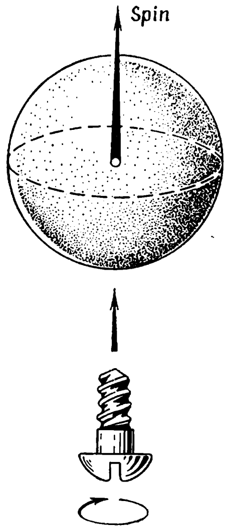

Fig. 4. Spin. The proper angular momentum of a particle is equal to $1/2\,\hbar$ for the electron, proton, and neutron.

tum numbers differ in their energies. This is due to the fact that the energy of interaction of the orbital magnetic moment with the external magnetic field depends on the value of the projection of the angular momentum onto the direction of the magnetic field, i.e. it depends on the magnetic quantum number (we will speak about it later). In the absence of an external magnetic field all states with different magnetic quantum numbers have the same energy, they are degenerate, i.e. merged together, non-discrete.

The electron has an angular momentum of its own equal to 1/2 and comparable with the orbital momentum. The electron resembles a toy top spinning about

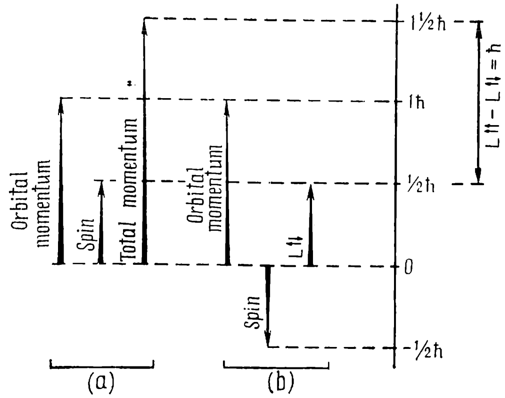

Fig. 5. The electron spin can have one of two orientations relative to the orbital momentum: parallel (*a*) and antiparallel (*b*). The total (orbital+spin) momentum with a parallel orientation exceeds by $\hbar$ that with an antiparallel orientation.

its axis. The proper angular momentum of an electron is called the *spin*. Since it is generally known that the angular momentum is measured in $\hbar$ units, we commonly say "the electron spin is equal to 1/2" (the $\hbar$ is omitted).

Imagine an electron rotating in an orbit. The spin may have the same direction as the orbital angular momentum, or the opposite direction. In the two orientations its magnitude differs by unity, i.e. by $\hbar$: the spin is also quantized. The *spin quantum number* m_z can assume one of two values: either $m_z=1/2$. when the spin and the orbital momentum are parallel, and $m_z=-1/2$, when they are antiparallel. In the two *s*-state, when the angular momentum is zero, the spin can also have two opposite directions. The angular

momentum of the nucleus (proton) serves as reference for the spin of an electron in the *s*-state.

We have by now stuffed your head with all kind of quantum numbers and the corresponding states. You will hardly keep them long in your head. But at this stage it is not so important, because we do not yet go deep into the description of quantum numbers. We will only say that they can be obtained with high precision from an equation derived in 1926 by the Austrian scientist E. Schrödinger. For his outstanding scientific achievements Schrödinger was elected Member of the USSR Academy of Sciences in 1934. The Schrödinger equation is of exceptional and fundamental importance in the physics of the microworld.

We will note in passing that other particles, besides the electron, have a spin of 1/2. One of such particles is the proton. Elementary particles having a spin of 1/2 are called fermions. None of the quantum states can be occupied by more than one fermion. This principle was formulated for the electron in the atom by the Swiss physicist Wolfgang Pauli in 1925. Later on, Fermi elaborated statistics for *all* particles with a spin of 1/2, i.e. fermions. He proved that the Pauli principle holds good for fermions in any systems, for instance for particles in atomic nuclei.

Hydrogen Atom Spectrum

When the hydrogen atom is in the normal (ground) state, the electron is in the innermost orbit, its energy being minimal. All the other states are excited, with the electron energy higher than in the ground state. To shift an electron from the first orbit to the second, about 10 electron-volts (eV) of energy has to be spent to overcome the electrostatic force of attraction be-

tween electron and proton. This can be done by bombarding the atom with electrons, whose energy should not be below the excitation energy; otherwise electrons hitting the atom will scatter elastically, without any loss of energy. Transition from the second level to the third requires much less energy, only about 2 eV. The further we go, the higher the rate of decrease in excitation energy. An electron receiving 13.53 eV completely loses its bond with the nucleus; this value is called ionization energy. As the principal quantum number (orbit number) increases, the spacing between energy levels rapidly decreases and they finally merge together when approaching the ionization energy.

The return of an electron from the outermost orbit (i.e. from the level corresponding to the ionization energy) to the innermost orbit is accompanied by emission of a photon with an energy of 13.53 eV. Transition from any other level to the first is attended by emission of a set of photons of different energies. Transition of an electron from any higher level to the second one causes emission of another set of photons, whose boundary energy is now about 3.5 eV instead of 13.53 eV, and so on. An emission spectrogram of atomic hydrogen reveals several series of spectrum lines, which are in different energy ranges.

Each emitted photon has its own frequency of electromagnetic oscillations and a definite wavelength, which can be found by dividing the light velocity by the frequency. The lines of each spectral series become denser towards the short-wave band.

The visible part of the light spectrum lies between wavelengths of about 4000 Å (dark violet) and about 7600 Å (the boundary of infrared glow). Light with a wavelength of 5500 to 6000 Å (from green to orange) is seen most clearly. In the hydrogen spectrum, the visible region contains just a few lines of the second

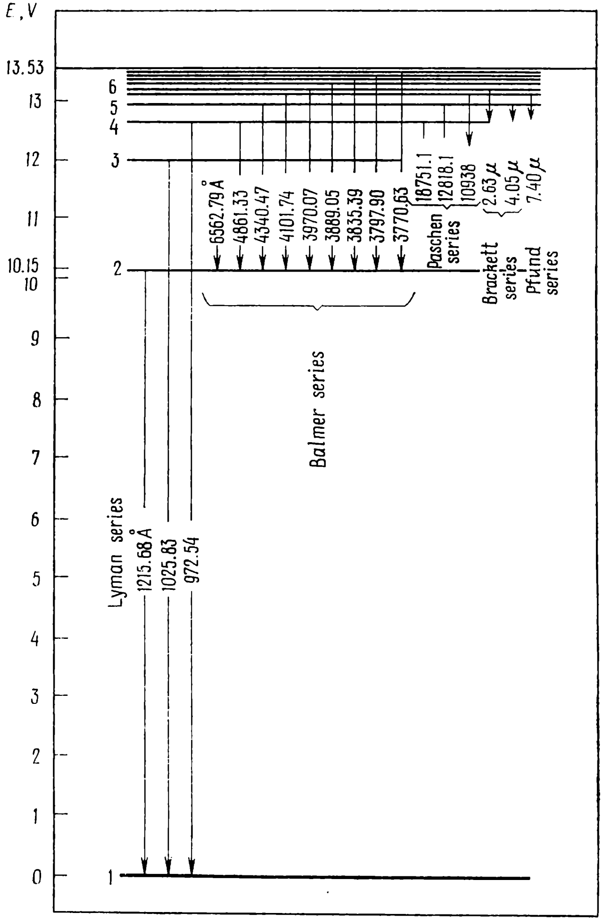

Fig. 6. Hydrogen atom energy levels (n) and transitions between them yielding the hydrogen atom spectrum.

series (transitions to the second level) called the Balmer series. The first, Lyman, series lies in the ultraviolet region. All the others, including the Paschen, Brackett and Pfund series, lie in the infrared part of the spectrum.

Each spectral series borders on a continuous spectrum extending towards the shorter wavelengths. The continuous spectrum adjoining, for instance, the Lyman line, appears because not only electrons from all upper orbits yielding separate spectral lines, but also free electrons, whose energy is not quantized and may take on any values, settle in the lower orbit. When such electrons land on the lower orbit, light quanta are emitted which may exceed the ionization energy by any value. When a great number of atoms emit light, a continuous spectrum appears, which adjoins the series boundary on the side of the higher energies (shorter waves). For the second, Balmer, series the continuous part of the spectrum is produced by electrons whose energy exceeds ionization energy from the second level and which is much lower (about 3.4 eV) than from the first level. Therefore the boundary of the Balmer series and the adjoining continuous spectrum lie in the range of larger wavelengths than for the Lyman series. For the Paschen series they are displaced still further towards the longer waves, etc.

The aforesaid refers to emission spectra. Absorption spectra, which have the same structure, are obtained when atomic hydrogen is subjected to continuous-spectrum radiation. Absorbing definite lines corresponding to transitions from the first level to higher ones, hydrogen yields the first series of the absorption spectrum. Transition from the second orbit to higher ones yields the second series of absorption lines, etc. In practical work absorption and emission

spectrograms show clearly only individual lines of the Balmer series.

It is interesting to note that better atomic hydrogen spectra are obtained from sources located on the sun than from those on earth. On the sun, for instance in protuberances, hydrogen is heated to extremely high temperatures which are difficult to obtain on earth. Only very recently did it become possible to obtain hydrogen plasma heated to extremely high temperatures in equipment designed for thermonuclear research.

We will now calculate the increase in hydrogen temperature when each of its atoms receives an energy of one electron-volt (1 eV$=1.6\times10^{-12}$ erg). Dividing one electron-volt by the Boltzmann constant, which is equal to 1.38×10^{-16} erg/deg, we obtain a temperature of 11 600° K. A more or less noticeable thermonuclear reaction requires a temperature corresponding to several tens of thousand electron-volts (several tens of kiloelectron-volts). Then the gas heats up to several hundred million degrees Kelvin. The physicists, however, prefer to measure the energy of particles, or their temperature, in electron-volts and kiloelectron-volts. Degrees are usually mentioned to strike one's imagination. Think only, hundreds of millions of degrees! But even at such high temperatures but a small fraction of the nuclei fuse together.

Nuclear physicists use an energy unit called the megaelectron-volt (MeV), which is equal to a million electron-volts. One MeV is 1.6×10^{-6} erg. The term "electron-volt" is due to the fact that an energy of 1 eV is gained or lost by an electron on crossing a potential difference of 1 V.

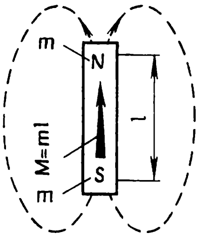

Fig. 7. Magnetic moment M is equal to the product of the magnetic charge in a magnet by the distance between the charges. In a straight magnet it is directed from the south to the north pole.

Magnetic Moments

We have already touched upon the magnetic properties of the electron and spoken about the magnetic quantum number. Now we will dwell in more detail on the magnetic moments of electron and proton.

A magnet, such as a magnetized rod or compass needle, is characterized by a magnetic charge and a magnetic moment, which is equal to the product of the magnetic charge by the distance between the magnetic charges in the magnet. Each magnet has two inseparable magnetic charges of opposite sign. Like charges of two magnets repulse each other, and unlike charges are attracted. The dimensionality of a magnetic charge is $[\text{force}]^{1/2} \times [\text{length}]$. This follows from the familiar Coulomb law as applied to magnetic charges which states, roughly, that the force of repulsion between two like magnetic charges is equal to the product of the charges divided by the square of the distance between them. The dimensionality of the magnetic moment is the square of length mul-

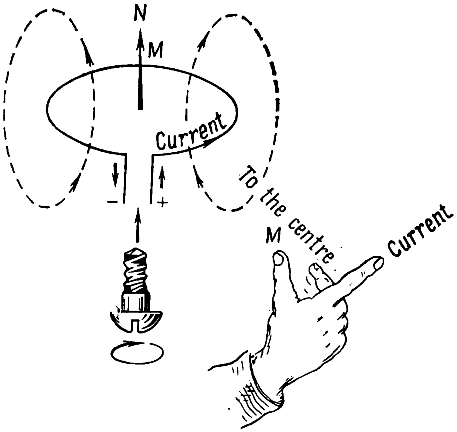

Fig. 8. The magnetic moment of a circular electric current, M, is equal to the product of the current intensity by the surface area encircled by the current. It is directed as shown by the thumb of the right hand if the middle finger points at the centre of the current circle and the index finger, along the direction of the current (from plus to minus, i.e. opposite to the movement of the electrons). The magnetic field of a circular current is equivalent to the field intensity of a straight magnet whose north pole is directed as the magnetic moment of the current. The direction of the magnetic moment of the current coincides with that of a right-handed screw perpendicular to the area encircled by the current and turning with the current (from plus to minus).

tiplied by force to a power of 1/2. Introducing the gauss (Gs)—the magnetic induction unit—we find that the magnetic moment is expressed in ergs per gauss (ergs/Gs).

A circular electric current sets up a magnetic field directed perpendicular to the plane in which the current flows. The magnetic moment of a circular current

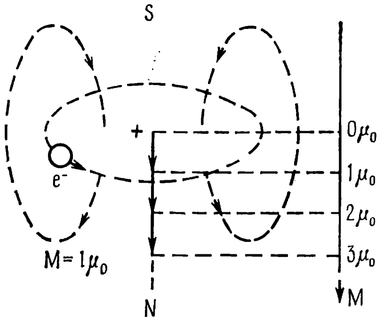

Fig. 9. The orbital magnetic moment of an electron assumes values multiple to the Bohr magneton μ_0 ($0\mu_0$, $2\mu_0$, etc.). It is caused by the motion of the electron about the nucleus.

is proportional to the product of the current intensity by the area around which the current flows. The magnetic moment is directed as a right-handed screw advances turning with the current. Recall that an electric current flows from plus to minus, i.e. in the direction opposite to the movement of the electrons. Perhaps it would be better to consider that the electrons move in the positive direction, but the direction of the current was adopted conventionally a long time ago, when the scientists did not know about the existence of the electron.

An electron orbiting around the nucleus is equivalent to a circular current. Therefore, when the orbital mechanical momentum is non-zero, a magnetic orbital moment appears. It is the greater, the higher the orbital momentum. Since the orbital mechanical momentum is quantized (acquires only discrete values), the magnetic moment is also quantized. The latter is equal to the orbital quantum number multiplied by Bohr magneton, i.e. the quantum of the ma-

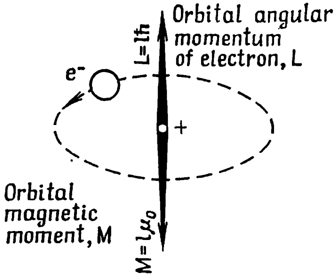

Fig. 10. Relative positions of the orbital angular momentum of an electron and the orbital magnetic moment.

gnetic moment of the electron which is equal to 0.927×10^{-20} erg/Gs.

But in addition to the orbital angular momentum the electron has an angular momentum of its own, the spin. There is a kind of a circular current also inside the electron itself, and the electron resembles a small electric magnet. Its own magnetic moment is equal to the Bohr magneton. It is significant that the ratio of the spin magnetic moment to the spin mechanical momentum is twice that of the orbital magnetic moment to the orbital mechanical momentum.

The spin of the proton (the hydrogen nucleus), as well as that of the electron, is equal to $1/2\,\hbar$. The charge of the proton is opposite in sign to that of the electron, therefore the magnetic moment of the proton is positive and has the same direction as the spin.

The mechanical momentum is equal to the product of the mass by the rotation velocity and by the distance from the rotation centre to the centre of gravity of the rotating mass. If we assume that the charge of a particle coincides geometrically with its mass, or, more precisely, that the charge is distributed exactly

as the mass, and if we take into account that the magnetic moment of a circular current is equal to the product of the current intensity by the area around which it flows, it becomes clear that when the mechanical momenta of two particles differing in mass but equal in charge are equal their magnetic moments will be inversely proportional to the masses of the particles. Indeed, suppose the mechanical momentum is equal to mvd (this value is the same for the proton and the electron, i.e. $1/2\ \hbar$); then for the proton, whose mass is 1836 times that of the electron, the product vd should be as many times as small. This value is proportional to the product of the current intensity (with equal charges) by the area encircled by the current; it is proportional to the magnetic moment. A magnetic moment which is 1836 times as small as the Bohr magneton, is termed the nuclear magneton. It is equal to 0.505×10^{-23} erg/Gs.

Formerly, the magnetic moment of the proton was expected to be exactly equal to the nuclear magneton, and the magnetic moment of the neutron (a particle having no electric charge), to zero. Measurements have shown, however, that the magnetic moment of the proton is 2.79 nuclear magnetons. The magnetic moment of the neutron is not zero, as was expected; it equals —1.913 nuclear magnetons. The surprisingly high magnetic moment of the proton points to its complex structure; in particular, the charge distribution in the proton does not coincide with its mass distribution. The central part of the proton is heavier, its charge is, so to say, more spread out, or "smeared", in space than its mass. Therefore the magnetic moment is higher than could be expected judging from the mechanical momentum. The fact that the neutron has a magnetic moment indicates that this particle is electrically neutral only on the average. The direc-

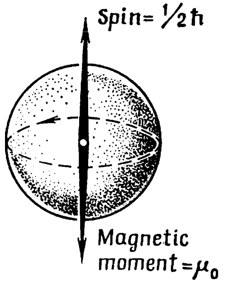

Fig. 11. The proper magnetic moment of an electron is equal to the Bohr magneton and directed opposite to the spin.

tion of the magnetic moment, which is opposite to that of the spin, shows that it is due to the negative charge. The positive charge, which compensates the neutral charge in the neutron, is so distributed that the magnetic moment set up by it is less than that of the negative charge.

We will mention one more peculiarity. If we calculate the ratio of the proper magnetic moment of the electron to the mechanical momentum (spin) according to the classical laws, it will turn out to be half the one observed experimentally. Incidentally, this circumstance stimulated the investigation which led to the determination of the value of the spin ($1/2\ \hbar$). A ratio of the spin magnetic moment to the spin mechanical momentum coinciding with experimental results is obtained from the electron theory taking into account Einstein's theory of relativity.

Imagine a set of excited hydrogen atoms. Suppose all the electrons in atoms are raised to a level with a principal quantum number of 2. In the absence of an external magnetic field the electrons at the $2s$-level

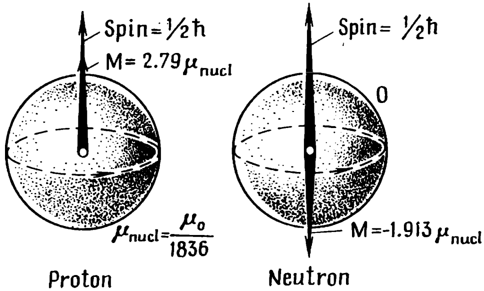

Fig. 12. Relative positions of the spins and magnetic moments of a proton and a neutron. The magnetic moment is expressed in Bohr magnetons, μ_{nucl}. The nuclear magneton is 1/1836 of the Bohr magneton.

(orbital quantum number $l=0$) may have their spins oriented along the magnetic field in certain atoms and opposite to the magnetic field in the others. We assume that the first kind of orientation is when the lines of force of an external field issuing from the north pole of the external magnet enter the south pole of a straight microscopic magnet (a rotating electron). With this orientation the electron energy is minimal, the electron occupying the most "comfortable" position. We will try to "switch" the electron by 180° in the direction opposite to that of the magnetic field. This will require work to be done in overcoming the attraction forces of the unlike magnetic poles and the repulsion forces of the like ones. In the second orientation (opposite to the field) the energy of the electron is slightly higher than in the first case. Consequently, in a magnetic field in the 2*s*-state two values of electron energy are possible which differ somewhat from the energy at this level in the absence of a field. A single *s*-level splits in two in a magnetic field.

In the $2p$-state the orbital quantum number is equal to unity. The electron possesses an orbital mechanical momentum. But it also has a spin momentum of $1/2\ \hbar$. The total angular momentum of the electron in the $2p$-state is equal to the sum of these momenta, i.e. 3/2. This **is** also the maximum magnetic quantum number at this level. The total mechanical momentum is associated with a certain magnetic moment. We have already noted that the mechanical momentum component directed along the magnetic field is quantized, its values can only be discrete, the adjacent values differing by unity, i.e. they are 3/2, 1/2, —3/2. As a result of quantization of the mechanical momentum the projection of the total magnetic moment onto the direction of the magnetic field is also quantized. This has actually given rise to the term "magnetic quantum number". Each of the components of the mechanical momentum and, hence, of the magnetic moment along the external magnetic field is associated with a definite value of electron energy. For one of the values, say 3/2, the electron energy is at a minimum because the magnetic moment is so situated that the lines of force issuing from the north pole of the magnet enter the south pole formed by rotation of the electron in its orbit and about its axis. If the magnetic quantum number is 1/2, the electron magnet slightly deviates from the direction of the magnetic field. The electron then receives a certain amount of energy. Turning the magnet to the position corresponding to —1/2 acquires still more energy. Shifting to the position precisely opposite to the magnetic field (—3/2) is accompanied by absorption of a maximum amount of energy. As a result, the energy level $2p$ splits into four sublevels in an external magnetic field.

How will the energy of the emitted light quanta

(photons) change on transition from the $2p$- to the $1s$-level? If the projection of the mechanical momentum onto the direction of the external magnetic field does not change on transition from the upper to the lower state, the energy of the emitted photon will evidently remain the same as it was in the absence of the magnetic field. When the transition is attended by a change in the magnetic quantum number, the photon energy changes too. If the projection of the quantum number is oriented "largely along the field" upon transition, the energy of the emitted photon increases, since a certain amount of energy is released as the magnetic moment is reoriented to a more "comfortable" position. The converse is true for reorientation to a less "comfortable" position, since it will require a certain amount of work. Thus, transitions from $+1/2$ to $+1/2$ and from $-1/2$ to $-1/2$ (the first figure denoting the magnetic quantum number at the higher, and the second, at the lower level) will yield a spectral line exactly the same as in the absence of the magnetic field. Transitions on which the magnetic quantum number increases by unity will yield a spectral line corresponding to a higher photon energy: these are transitions from $-1/2$ to $1/2$ and from $1/2$ to $3/2$. The work expended previously to bring the magnetic moment to the "uncomfortable" position is recovered and added to the photon energy, since the new position is more "comfortable" and corresponds to a lower electron energy. Transitions on which the magnetic quantum number decreases by unity (from $1/2$ to $-1/2$ and from $3/2$ to $1/2$) are accompanied by emission of a weaker photon, because here part of the energy is spent on turning the magnetic moment to a less "comfortable" position. This shift requires expenditure of some energy, which is subtracted from the energy of the emitted photon. The appropriate

spectral line shifts towards the larger wavelengths exactly by as much as the line whose emission is attended to by an increase in the magnetic quantum number by unity shifts towards the smaller wavelengths.

Note that transitions upon which the magnetic quantum number would change by 2 (for instance, from $+3/2$ to $-1/2$) are impossible. The magnetic quantum number can never change by more than unity in a single act. Thus, in a magnetic field the spectral line corresponding to transitions from the $2p$- to $1s$-level splits into three lines. For higher levels, for instance the initial one corresponding to the principal quantum number 3 and orbital quantum number 2, it splits into more lines. The $3d$-level (orbital quantum number 2) splits into six levels (magnetic quantum numbers $5/2$, $3/2$, $1/2$, $-1/2$, $-3/2$, $-5/2$); transitions to four levels corresponding to the $2p$-level (magnetic quantum numbers $3/2$, $1/2$, $-1/2$, $-3/2$) yield a greater number of combinations with different spectral line energies, the changes in the magnetic quantum number not exceeding unity.

The splitting of spectral lines in an external magnetic field was discovered as far back as 1896 by the Dutch scientist P. Zeeman when investigating the radiation spectrum of sodium. A rigorous explanation of the Zeeman effect could not be given until quantum mechanics was fully developed.

The Zeeman effect yields indirect information on the energy levels of the electrons in the shells associated with discrete values of the projection of the electron magnetic moment. In 1922 the German scientists O.Stern and W.Gerlach proved by direct experiments the existence of discrete values of the electron magnetic moment in an unexcited atom. Passing atoms of silver, in whose outermost electron shell the unexcited

electron is in the s-state, through a non-uniform magnetic field, they discovered that half of the atoms were attracted to one pole of the magnet, and the rest, to the other. The deviation of the beam one way or the other precisely coincides with the calculated deviation, provided the electron possesses a magnetic moment equal to the Bohr magneton and having two possible orientations, parallel and antiparallel to the magnetic field.

It is worth mentioning that a procedure for determining the magnetic moment of the atom, similar to that applied by Stern and Gerlach, had been proposed by the Soviet scientists P. L. Kapitsa and N. N. Semenov (who later became Academicians) in a paper published as early as December 1920.

Basic Principles of Quantum Mechanics

The above description of the quantum numbers and states of the electron in the hydrogen atom is too simplified and resembles the description of the motion of a particle in classical mechanics. To give you a better insight into the subject, we will tell you the principles underlying quantum mechanics, i.e. the principle of superposition of states and the uncertainty principle. These principles were deduced by generalization of experimental data typical of the microworld.

In quantum mechanics, it is always understood that a particle (electron, proton, neutron, etc.) for which there are several possible (allowed) states can be in several of these states, or even in all of them, simultaneously. In fact, one cannot, for instance, assert,

as was done above for simplicity sake, that the electron is in the first shell only (the principal quantum number is equal to unity). There is always some probability that the electron is in two, three or even in all the possible states simultaneously. This means that there is some chance (which is different for different states) of finding the electron not only in the first shell, but in any of the others as well. For heavy atoms there is even a probability of finding the electron inside the nucleus. This probability explains the capture of the electron by the nucleus, the so-called *K*-capture (the electron is captured by the nucleus from the *K*-shell), as a result of which one proton in the nucleus turns into a neutron. An electron can never be found between shells. The state between shells is not one of probable or possible states of the electron.

In quantum mechanics, the state of an electron (proton, neutron, etc.) is characterized by a certain function Ψ, which is called the wave function. The main goal of quantum mechanics is to determine this function. It is found by solving the Schrödinger equation if the particle velocity is low as compared to the light velocity. When this is not so, another equation is used in the case of the electron; this equation was derived by P. Dirac, one of the founders of quantum mechanics.

Each one of the possible states of a particle is described by the appropriate function: Ψ_1, Ψ_2, Ψ_3, and so on. The number of such functions may be very great, sometimes even infinite. For an electron bound in an atom the possible states are discrete, i.e. they differ by a finite value. In the hydrogen atom each of the states differs from another by at least one quantum number. No two states have the same quantum numbers throughout.

If an electron is free, it can have an indefinite number of ground states. The spectrum of the ground states of a free electron is not discrete, it is continuous.

The true state of an electron is defined by the sum (superposition) of its possible ground states: Ψ_1, Ψ_2, and so on, each of which is taken with its own weight (probability).

The wave function of a particle whose ground states are defined by proper functions Ψ_1, Ψ_2, Ψ_3, etc., is equal to

$$\Psi = a_1\Psi_1 + a_2\Psi_2 + a_3\Psi_3 + \ldots \tag{2}$$

Here, the factors a_1, a_2, a_3, etc. determine the weight (the probability of finding a particle) in the states Ψ_1, Ψ_2, Ψ_3,... respectively. Equation (2) describes the superposition of states. This superposition is linear, all the proper functions in it are to the first power. To find the wave function, one should first determine the complete set of proper functions Ψ_1, Ψ_2, ...

The mathematical tools of quantum mechanics are highly developed. This science is one of the most harmonious and perfect creations of the human genius. It enables solving problems of fundamental importance for present-day technology.

Recalling the superposition principle, we should visualize the electron in the atom as a more "smeared-out" entity than in the classical analogy. The electron appears to be spread out, distributed over different states. It is distributed non-uniformly, the probability of finding it in some states is particularly high, while for the others it is lower. But the electron is not divided into parts distributed over different states. Measurements show that it resides wholly in one state; only the probability of finding it in one state or another is different. Another principle of quantum mechanics is still more unusual; it is the uncertainty

principle described below in the section "Uncertainty Relation and Virtual Processes".

The uncertainty relation, which is the mathematical expression of the uncertainty principle, implies that if we determine the precise position of an electron (or any other particle), we can say nothing about its impulse (and kinetic energy). It may have any value. And conversely, if we define the exact value of the impulse (kinetic energy), we can say nothing about the position of the electron: it may be found at any point of space with equal probability. In other words, an electron cannot have accurate values of coordinate and impulse simultaneously. The minimum product of uncertainty in impulse by uncertainty in coordinate has quite a definite value, which is independent of the state of the art in measuring technique because it is inherent in the quantum-mechanical nature of these magnitudes. Incidentally, the uncertainty principle, as well as the principle of superposition of states, also leads to the "smearing out" of a microparticle: it is impossible to indicate, for instance, the absolutely exact position and the precise boundaries of an electron (indeed, they do not exist); this would lead to an infinite uncertainty of its impulse and kinetic energy. Such properties of the microworld cannot be tangibly visualized. They became known to man only after many incontestible experimental proofs had been obtained.

In the following sections we will repeatedly resort to classical analogies when describing microworld phenomena. The reader himself will have to introduce corrections stemming from the principle of superposition of states and from the uncertainty relation.

Radio Emission of Hydrogen on the 21.1-cm Wavelength

An ordinary cool hydrogen atom can be a source of radio emission. In the lower state, which corresponds to the principal quantum number 1 and orbital number 0 (*s*-state), the electron spin in the hydrogen atom can be oriented in either of two directions relative to the nuclear spin.

The electron and proton spins may be parallel or antiparallel. No other relative positions of the spins are possible. The electron spin is oriented relative to the nuclear spin because there are no other references, such as the orbital momentum in the *s*-state. An electrostatic force of attraction acts between electron and proton; it is the main force. In addition there is a relatively weak magnetic force acting between electron and proton which depends on the mutual orientation of the magnetic moments of the electron and nucleus. When the spins of the electron and nucleus are parallel, i.e. when the magnetic moments are antiparallel, the force of attraction between electron and proton is stronger than with the antiparallel arrangement of the spins, and the electron-proton binding energy is higher. Thus, when the spins of the electron and proton are reoriented from the antiparallel to the parallel position, the bond between these two particles increases, and the difference between the energies with antiparallel and parallel orientations is emitted in the form of a photon. The emitted energy is low, therefore the emission frequency is also low and the wavelength is large in relation to the other waves emitted by the hydrogen atom, for instance, those of light radiation. But from the standpoint of radio engineering this is still a short

wave. The wavelength of radio emission of cool atomic hydrogen is 21.1 cm and the frequency 1420.406 MHz.

An interesting question arises: why are all electrons in all hydrogen atoms not in a spin-parallel position? Indeed, the lower (parallel) level is more advantageous energy-wise and, since there is emission, all atoms will gradually shift to the lowest state. To transfer them to higher energy states (spin-antiparallel), some work has to be done. How do we obtain the energy required? The point is that hydrogen atoms collide with each other. The collision energy is almost always higher than the energy of transition to a higher energy state. On collision, the spins take either parallel or antiparallel positions at the expense of the kinetic energy of collision. The energy is then distributed uniformly over the degrees of freedom. With the parallel arrangement of the spins there is a characteristic direction, i.e. the direction of the total spin. This spin can be oriented in one of three ways in accordance with the three directions in space; therefore the parallel spin has three degrees of freedom. With antiparallel spins there is no characteristic direction (the total spin is zero), and this state has only one degree of freedom. Therefore, if collisions are frequent enough, each atom with antiparallel (nuclear and electron) spins is associated with three atoms having parallel spins. The emission of a radio wave tips the scale towards parallel orientation, while collisions restore the original relationship.

Radio emission of atomic hydrogen was predicted in 1945. In 1951 it was observed in radio emission reaching the earth from outer space. Since then interstellar research and, in general, investigations of the universe with the aid of the 21.1-cm wave have become one of the principal tools of radioastronomy.

Our Galaxy—the stellar system of the Milky Way

to which our sun belongs—contains over 100 000 million stars, the diameter of its disk is equal to about 50 thousand light years. The light year is a measure of distance. If we convert the Galaxy diameter to familiar units of length, it will be about 10^{23} cm. The entire space between stars is filled with rarified hydrogen whose density is about 1 atom/cm^3. (The mean density of matter in the universe is much lower. According to one of the estimates one nucleon is associated with about 100 litres of volume on the average.) With this density, collisions between hydrogen atoms are very rare, the equilibrium between the parallel and antiparallel orientations of the spins is restored within several hundred years. But considering that the time of spontaneous transition from the "uncomfortable" orientation of spins to a more "comfortable" one is very great, about ten million years, the restoration of equilibrium in interstellar hydrogen occurs rapidly enough. Within ten million years it is restored many times.

A new question arises, however: wouldn't radio emission be too weak, since transitions and emission are very rare? With a density of 1 atom/cm^3, a volume of 1 cm^3 will release one quantum in ten million years. But the vast dimensions characteristic of outer space save the situation. Over a distance of 10^{16} cm (a ten-millionth fraction of the Galaxy diameter) and with a gas density of 1 atom/cm^3, the total atomic cross section is equal to 1 cm^2. Here, a column of length 10^{16} cm and cross section 1 cm^2 will release 100 quanta/s. Because of the vast dimensions of the Galaxy one can even speak of investigating the surface layer of some galactic region or other, although this surface layer is of incredible thickness by our terrestrial standards.

Radio waves of length 21.1 cm reaching us from

different parts of the Galaxy enabled scientists to measure the distribution of hydrogen density in it. They made use of the relationship between radiation intensity and density: the radiation intensity is proportional to the density of atomic hydrogen. The larger the number of atoms, the stronger the radiation. These measurements required the use of complex devices, because many other waves arrive from space as well as 21.1-cm waves. In particular, strong radiation of different wavelengths is emitted by completely ionized hydrogen. An electron, when flying near a proton, changes its flight path, this being accompanied by the emission of a radio wave.

Using the 21.1-cm wave it is possible to measure not only the density of hydrogen but also the velocity of its motion. If a layer of hydrogen emitting a 21.1-cm wave moves toward the earth, the wave frequency slightly increases; this is the familiar Doppler effect observed when a whistling train is approaching and receding. The pitch increases in the former case and drops in the latter. The radio-wave frequency changes in a similar way. By accurate measurements of the wavelengths (frequencies) of radio waves issuing from different regions of the Galaxy scientists determined the velocities with which it rotates around its centre. The structure and velocities of the Magellanic clouds were precisely determined in much the same way. The Magellanic clouds are two interconnected stellar agglomerations closest to our Galaxy which are located about 70 and 83 thousand light years away from the sun. The dimensions of these agglomerations are gigantic, even by cosmic standards. The light year, as has been noted above, is the distance covered by light within one year, i.e. 9.46×10^{12} km. Incidentally, astronomers use this unit very seldom, the astronomical unit of

distance being the parsec, which equals 3.26 light years. There is also a relatively small length unit used in measurements within the solar system; it is termed the astronomic length unit and is equal to the mean distance from the sun to the centre of gravity of the earth-moon system. Its precise value, 1.495993×10^{11} m, has been determined by Soviet scientists.

In the Southern Hemisphere the Magellanic clouds can be seen with the naked eye. They are of great interest to astronomy: besides most diverse stellar systems, including dwarf galaxies, they contain gas nebulae. By measuring the decrease and increase in the length of radio waves of atomic hydrogen issuing from different regions of the Magellanic clouds, radioastronomers have determined the rotation velocities of the both galaxies and found that the motion of these clouds is correlated.

With the aid of radio emission of atomic hydrogen it is possible to measure the temperature of interstellar hydrogen. The higher the temperature, the greater the velocity of hydrogen atoms. But thermal motion is a random motion. In thermal motion atoms move in different directions, their velocities correspond to a given temperature only on the average. Due to the Doppler effect the emission from atoms involved in thermal motion does not have a strictly defined frequency, the aerial receives waves differing in frequency from those corresponding to the emission of an atom at rest. The radio emission line is smeared out, and the higher the temperature of the emitting hydrogen the more it is spread. By measuring the line width one can determine the temperature of interstellar hydrogen. In our Galaxy it is slightly above 100°K as distinct from theoretical predictions of 30 to 60°K. Here we imply the temperature of inters-

tellar hydrogen. The temperature of hydrogen in zones where active processes take place is much higher.

Professor I. S. Shklovsky, the prominent Soviet astronomer, expressed interesting ideas about the possibility of existence of rational beings on other planets. Of course, he does not mean planets of the solar system, such as Mars or Venus, which figure in science-fiction stories. Proceeding from scientific data Shklovsky believes that within a sphere of radius of 100 light years there may be one or two planets where the conditions of life are similar to those on earth. These planets may be inhabited by rational beings, who will probably attempt to communicate with other planets. Shklovsky and other scientists arrive at the conclusion that rational beings will inevitably attempt to get in contact with other worlds by using the 21.1-cm wave. In terrestrial conditions, hydrogen is a very weak source of radio waves; no doubt, conventional generators will be used for this purpose. The 21.1-cm wave has been selected because the receivers of radio astronomers in other worlds are supposed to be tuned to it. Projects are being developed for continuous reception of waves from outer space on the 21.1-cm wavelength in those directions where the existence of worlds inhabited by rational beings is most probable. Highly organized inhabitants of other planets are likely to use this wavelength for transmitting some kind of a simple code or number proving their rationality. For instance, the number π, or the base of the natural logarithm, $e=2.718$, and so on. They expect to receive similar signals from others.

'It could be assumed', writes Shklovsky, 'that the highly organized rational inhabitants of some planets have continuously and for tremendous intervals of time kept the main lobes of their gigantic aerials

"aimed" at a certain number (say 100) of comparatively near stars, where they presume the possibility of rational life, in the hope of receiving a response.'

The radio wave of hydrogen may prove to be not only an extremely powerful tool of radio research of outer space, but also a link connecting rational beings inhabiting different solar systems.

Deuterium, Tritium, Neutron

Besides ordinary hydrogen, there is heavy hydrogen—deuterium, which is now used in nuclear engineering as an explosive and which will in the future serve as fuel for thermonuclear power plants. Heavy hydrogen was discovered in 1932; its electron shell does not differ in any way from that of usual hydrogen (it contains only one electron), but its nucleus is about twice as heavy as that of ordinary hydrogen.

To say "the electron rotates about the nucleus" is not quite correct. In actuality the electron and nucleus rotate about their common centre of gravity. Since the proton mass is 1836 times that of the electron, the centre of gravity of the hydrogen atom is very close to the centre of the nucleus, but still does not coincide with it. In deuterium, the mass of the nucleus is twice that of the proton, and the centre of gravity of the nucleus-electron system is still closer to the centre of the nucleus. If the mass of the nucleus were infinitely large, the centre of gravity would precisely coincide with the centre of the nucleus. The difference in the positions of the centre of gravity in atoms of ordinary and heavy hydrogen, although small, changes the energy levels of electrons in the atom. Therefore, the spectral lines of deuterium are slightly displaced relative to the lines of ordinary

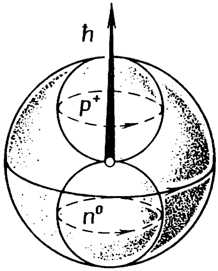

Fig. 13. The deuton consists of a proton and a neutron. The deuton spin is equal to unity.

hydrogen. This displacement can be accurately determined. The existence of deuterium was proved when the measured displacement precisely coincided with the one calculated for a nucleus twice as heavy as that of hydrogen. Heavy hydrogen for spectral experiments is obtained by evaporating a great amount of liquid hydrogen. Ordinary hydrogen evaporates more readily, and the remainder is enriched in heavy hydrogen.

The nucleus of deuterium, the deuton (or deutron), consists of two firmly bound particles, a proton and a neutron (a neutral particle). The neutron was discovered in 1932 by the British scientist James Chadwick. The neutron mass—1838.6 electron masses—slightly exceeds that of the proton. Accordingly, its inherent energy (product of the mass by the square of the light velocity) is higher as well. Outside nuclei, the neutron is unstable, its mean life up to disintegration into a proton, an electron and a neutrino (more precisely, antineutrino, another elementary particle) is equal to 17 min. The mean life of the neutron is approximately equal to the time within which the

initial number of neutrons decreases 2.7 times or, more precisely, e times. Unstable particles are also characterized by a half-life, the time during which half of the initial amount of matter disintegrates. The half-life of a free neutron is 11.7 min according to the measurements of the Soviet scientist P. Spivak, who received for this work the Gold Medal and, together with Yu. Prokofiev, the Kurchatov Prize for 1962. In order to express the half-life in terms of mean lifetime, the half-life should be divided by the ratio of the logarithm of 2 to the logarithm of e, i.e. by 0.693. To convert the mean lifetime to the half-life, the mean lifetime should be multiplied by 0.693. According to Spivak, the mean lifetime of the neutron is 11.7/0.693, i.e. 16.9, or approximately 17 min.

Of all the hydrogen contained in nature 0.999844 is accounted for by ordinary hydrogen and 0.000156, or 0.0156%, by heavy hydrogen. When people learn to use thermonuclear energy for peaceful purposes, mankind will possess an unlimited source of power. If all the deuterium contained in the oceans of our planet were burned in thermonuclear reactors, the amount of energy released would be one hundred million times higher than the heat of combustion of all the earth's fossil fuel (coal, petroleum, gas, peat). Here, we estimate the world's reserves of fossil fuel at 6 000 000 million metric tons of reference fuel with a caloric value of 7000 kcal/kg.

Nuclei with the same electric charge but differing in mass are termed isotopes. Ordinary and heavy hydrogen are stable isotopes of hydrogen. In 1939, L. Alvarez and R. Cornogue (USA) bombarded heavy hydrogen with neutrons and obtained an artificial hydrogen isotope, tritium, whose nucleus consists of one proton and two neutrons.

Tritium is unstable; it disintegrates, emitting an electron and an antineutrino and turning into helium-3, the light isotope of helium. Large amounts of tritium are obtained in nuclear reactors by irradiating lithium-6 with slow neutrons. On capturing a neutron, lithium-6 disintegrates into helium and tritium.

Owing to its high radioactivity and volatility tritium presents a great hazard to man.

Positron, Antiproton, Antineutron, and Antihydrogen

In 1928, the British theoretician Dirac, a very young man then, predicted the existence of a positively charged electron—the positron. This particle was not actually discovered until 1932, when K. Anderson (USA) found it in cosmic rays. A few years previously the particle had been observed by the Soviet scientist D. Skobeltsyn in a cloud chamber improved by him. Unfortunately, his photographs, on which one could see positron tracks, were not published in due time.

In the cloud chamber, oversaturated vapour is formed. A charged particle passing through the chamber ionizes the vapour, forming condensation centres. It leaves in its wake a track of mist drops. The track is photographed with an ordinary camera. By placing a camera in a magnetic field Skobeltsyn recorded the sign of the charge. The magnetic field makes the paths of particles of unlike charge deviate in opposite directions. The curvature of the track indicates the magnitude of the charge or mass and energy of the particles. A positron is born together with an electron when a gamma-quantum slows down in a heavy

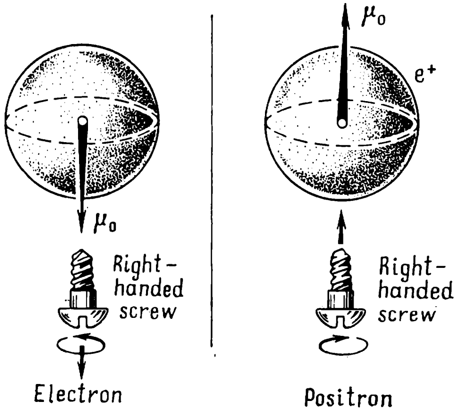

Fig. 14. The direction of the magnetic moments of the electron and the positron.

substance, for instance a lead plate. The newly born pair leaves two symmetric tracks issuing from the same point and curved in opposite directions.

High-energy particles are slowed down inefficiently in the cloud chamber. The density of the vapour in it is too low. For recording fast particles use is made of the bubble chamber, in which a supercooled vapour is supplanted by an overheated liquid—liquid hydrogen, propane, pentane, etc. Owing to ionization, a particle forms a bubble track showing the path of the particle. In current experiments tens and hundreds of thousands of photos of particle tracks in bubble and cloud chambers are made and developed.

Let us now revert to the positron. It has the same mass as the electron and the same spin, 1/2. The positron is stable and its lifetime is infinitely long. A positron and an electron, when colliding, annihi-

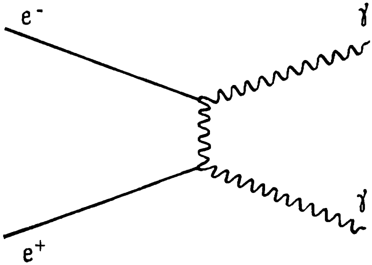

Fig. 15. Electron-positron annihilation into two photons.

late and turn into two (sometimes three) photons, particles having no rest mass. The energy of each of the two photons formed is easy to calculate: the rest mass of the electron should be multiplied by the square of the light velocity. We obtain $9.1 \times 10^{-28} \times$ $\times 9 \times 10^{20} = 0.82 \times 10^{-6}$ erg; converting this to mega-electron-volts $(0.82 \times 10^{-6}/1.6 \times 10^{-6})$, we find that the photon energy is approximately 0.51 MeV.

To start a reverse reaction (birth of a pair), double the energy is required—about 1 MeV (1.022 MeV).

After the positron was discovered the physicists came to the conclusion that each elementary particle should have an antiparticle. This proved to be true: the proton has the antiproton, the neutron has the antineutron, and so on. Only three exceptions are known, one of them being the photon, which is a particle and an antiparticle simultaneously. The other two exceptions are the π^0- and η-mesons.

Experimental observation of antiprotons and antineutrons became possible after gigantic proton accelerators were built. An antiproton is born when a proton possessing a kinetic energy of at least 5.6 GeV (5600 million electron-volts) collides with another proton. This energy is called the antiproton birth

threshold. The threshold is much higher than the proper energy of the antiproton, which is approximately 1 GeV. This is due to the fact that several laws of conservation operate when an antiproton is being born. For instance, if a particle with a negative charge appears, a positively charged particle is born as well. The appearance of a new particle is accompanied by the birth of an antiparticle of the same mass. The reaction of formation of new particles should obey the law of conservation of angular momentum. When a target is at rest and an accelerated proton hits it, the initial angular momentum is equal to the product of the proton mass by its velocity. The reaction products should possess the same angular momentum, i.e. should have a definite velocity and, consequently, kinetic energy. As a result, the original proton should have an energy of at least 5.6 GeV, although the proper energy of the antiproton being born is about 1 GeV.

When calculating the antiproton birth threshold one takes into account the effects stemming from the theory of relativity—relativistic effects. According to the theory of relativity the velocity of a particle cannot exceed the light velocity. No matter how great the kinetic energy of a particle possessing a rest mass, its velocity is always below the light velocity, though the difference may be very slight indeed. But the kinetic energy is equal to half the mass of the particle multiplied by the square of its velocity. Since the velocity of a particle does not increase with kinetic energy and remains below the light velocity, its mass grows. Relativistic effects become extremely important when the kinetic energy is comparable with the proper energy of the particle (m_0c^2); for the electron it is equal to 0.51 MeV, for the proton 938.2 MeV, or about 1 GeV. When the

kinetic energy is equal to the proper energy of the particle, its mass exceeds the rest mass by over 2.4 times and its velocity equals 91% of the light velocity. An increase in kinetic energy up to two proper energies increases the particle mass to about 4.2 rest masses and the velocity, to 97.26% of the light velocity.

In the relativistic region the impulse of a particle is approximately proportional to its kinetic energy (since the mass of a particle is proportional to its energy); it depends on the energy to a greater extent than in the low-energy region, where the impulse is proportional to the square root of the kinetic energy. Therefore, in the relativistic region a particle carries a relatively higher impulse than in the non-relativistic region. Hence, according to the law of conservation of impulse, the collision products have a higher impulse, they retain a relatively greater kinetic energy than in the non-relativistic region.

The minimum energy (threshold) required for the birth of a pair of particles (particle A and antiparticle $\tilde{A}$) of equal mass on collision of a proton with a proton at rest (the target) is equal, all effects considered, to

$$T_{min} = 2m_A \left(\frac{m_A}{m_p} + 2\right) c^2 \tag{3}$$

When a proton-antiproton pair is born, then

$$T_{min} = 2m_p \left(\frac{m_p}{m_p} + 2\right) c^2 = 6m_p c^2$$

Converting this figure into gigaelectron-volts, we obtain the above figure of 5.6 GeV characterizing the antiproton birth threshold.

Present-day proton accelerators are so constructed that nucleon-antinucleon pairs can be formed there. The term "nucleon" embraces the proton and the

neutron, which make up the nuclei. In 1954 a synchrotron was built in Berkeley (California) producing 6.2-GeV protons. Later, accelerators with a higher proton energy were built which were designed for obtaining particles heavier than nucleons. In the USSR (Dubna) a 10-GeV accelerator has been operating since 1957. In Switzerland and the USA accelerators for 28 and 33 GeV, respectively, were built in 1959 and 1960. In the USSR a gigantic accelerator for 70 GeV was built in 1967.

M. Pentz of the European Council for Nuclear Research (CERN) gives some data on high-energy accelerators built and to be built. These data are reproduced in Table 1.

Efficient investigation of elementary particles, which requires accelerators, can only be carried on either by highly economically and technically developed states or by associations of countries. Naturally, both capitalist and socialist countries cooperate in this investigation. This has given rise to such huge international research centres as the CERN in Switzerland and the Joint Institute for Nuclear Research in the USSR.

Despite the powerful equipment available the scope of production of new particles is rather limited. The prominent physicist Emilio Segré wrote that in 1955 only one antiproton could be obtained each 15 min on the Berkeley synchrotron. Then, after five years of improvement in the experimental procedure, it became possible to produce ten antiprotons per minute in Berkeley. One particle each six seconds.

The antiproton is equal to the proton in mass, it is charged negatively. It is a stable particle. Its spin is 1/2, the same as that of the proton. Colliding with a proton, an antiproton may, in rare cases, scatter elastically, i.e. deviate from its path. When

TABLE 1

HIGH-ENERGY ACCELERATORS*

Location	Accelerator type	Year of completion (actual and planned)	Energy, GeV
Brookhaven, USA	Proton synchrotron	1952	3
Birmingham, UK	ditto	1953	1
Berkeley, USA	ditto	1954	6
Cornell, USA	Electron synchrotron	1955	1.2
California, USA	ditto	1956	1
Dubna, USSR	Proton synchrotron	1957	10
Paris, France	ditto	1958	2.5
Frascati, Italy	Electron synchrotron	1959	1.2
Geneva, Switzerland	Proton synchrotron	1959	28
Brookhaven, USA	ditto	1961	33
Moscow, USSR	ditto	1961	7
Princeton, USA	ditto	1962	3
Cambridge, USA	Electron synchrotron	1962	6
Harwell, UK	Proton synchrotron	1963	7
Kharkov, USSR	Linear electron accelerator	—	2
Erivan, USSR	Electron synchrotron	—	6
Serpukhov, USSR	Proton synchrotron	1967	70
Hamburg, FRG	Electron synchrotron	1963	6
Argonne, USA	Proton synchrotron	1963	12.5
Stanford,USA	Electron linear accelerator	1966	45
Batavia, USA	Synchrotron	1971	200
Geneva, Switzerland	Proton synchrotron	1975	300

* For brevity sake only accelerators for over 1 GeV are included

a proton encounters an antiproton the electric charges of the two particles may be neutralized. This reaction is called recharge. In this case, the proton and antiproton give birth to a neutron and antineutron. This is how antineutrons were obtained in 1956. The antideuton was discovered in Brookhaven in 1965

by bombarding a beryllium target with 30-GeV protons. This was the first complex antineucleus. Its existence shows that the intranuclear forces in antinuclei are of the same nature as in nuclei, i.e. the nuclear forces, as we say, are invariant to charge conjugation.

An antiproton and a proton annihilate on collision. They transform into other forms of matter. In contrast to electron-positron annihilation they do not turn into photons at once or completely. Antiproton-proton annihilation involves a chain of transformations. At first several (up to 6, 7 or 8) pi-mesons (or pions for short) are formed. As you will see below, pi-mesons play a very important part in the structure of matter; they determine the nuclear forces binding nucleons in the nuclei. There are positively and negatively charged pi-mesons, there is also a neutral pi-meson. Negative pi-mesons are antiparticles relative to positive pi-mesons; each has a mass of 273 electron masses (em). The mass of the neutral pi-meson is 264 em, it is a particle and an antiparticle at the same time. This is the second (after the photon) exception from the general rule that each particle should have an antiparticle. No pi-meson has a spin.

A neutron and a antineutron annihilate in a similar way. Therefore one may also speak of annihilation of a nucleon-antinucleon pair.

The disintegration of a nucleon-antinucleon pair into pions is the first step of the transformation cascade. Strictly speaking, this disintegration may be a second step. Sometimes, very short-lived (10^{-22} to 10^{-23} sec) particles are formed together with pi-mesons on nucleon annihilation; these particles are a neutral omega-particle with a mass of 1530 em, which disintegrates into three pi-mesons, and a rho-particle with nearly the same mass (about 1490 em) disintegra-

ting into two pi-mesons. The rho-particle may be positive, negative or neutral. Theoretical physicists have already for some time supposed that the nucleon contains an omega and a rho-particle. Experimenters discovered them in 1961. Short-lived particles cannot be observed directly by means of instruments, the problem of their existence is solved by calculating the energy and impulse distribution of long-lived products of nuclear reactions with the use of a special procedure. The omega-meson was found when investigating the impulse and energy (mass) distribution of pi-mesons obtained on antiproton-proton annihilation and taken in combinations of three particles. The rho-meson was discovered when investigating the energies and impulses of pi-mesons (taken pairwise) formed on collision of a negative pi-meson with a proton. Incidentally, experimenters found not only particles predicted by theoreticians. In investigating the collision of a positive pion with a deuton researchers found the so-called eta-zero-meson in the reaction products; this is a neutral, short-lived particle with a mass of about 1070 em disintegrating into three pions—positive, negative and neutral. The eta-meson, however, lives longer than the omega- and rho-mesons, 10^{-18} to 10^{-19} sec. Short-lived mesons are also called resonances. Similar particles with a lifetime of the order of the nuclear lifetime (10^{-23} sec) are also observed on interaction of various mesons with heavy particles, for instance on scattering. The mass of these particles is higher than that of the nucleon.

Investigation of resonance particles, both mesons and heavier-than-nucleon particles, has lately become a powerful tool in studying so-called strong interactions between particles. These interactions will be described in one of the following sections. Special

sections deal with resonance particles, whose number has already reached over two hundred, including the resonance antiparticles.

Let us now revert to proton-antiproton annihilation. In this process only a small fraction of the events involve omega- and rho-particles. Keeping this in mind and also remembering that the stage which includes the disintegration of omega- and rho-particles is very short-lived, we will assume for simplicity that pions are formed directly from a nucleon-antinucleon pair.

The second stage (the first stage of annihilation is the formation of pi-mesons) is disintegration of pi-mesons. A positive pi-meson, having lived, on the average, 2.6×10^{-8} sec, disintegrates into a positive mu-meson and a neutrino. After the same period a negative pi-meson splits into a negative mu-meson and an antineutrino. A positive and a negative mu-meson are a particle and an antiparticle relative to each other. There is no neutral mu-meson. A neutral pi-meson disintegrates directly into two photons, by-passing the intermediate stages.

It was due to a misunderstanding that mu-mesons were classed with mesons, i.e. particles intermediate in their properties between nucleons and electrons. Actually, it is pi-mesons that can be considered as intermediate particles. Mu-mesons are similar to electrons in all their properties; they differ from electrons only by their tremendous mass (207 em) and instability—their lifetime is 2.2×10^{-6} sec. Their spin is 1/2, i.e. the same as that of the electron. Mu-mesons might be called heavy electrons. True, there is one more, finer and deeper difference between the muon and the electron. But we will speak about it later, in the section on experiments with muon neutrinos.

The third stage of transformation of a nucleon-

antinucleon pair is disintegration of mu-mesons into three particles each: an electron, a neutrino, and an antineutrino. A negative mu-meson disintegrates into an electron, a neutrino, and an antineutrino; a positive one, into a positron, a neutrino, and an antineutrino.

Finally, electrons and positrons annihilate (the fourth stage), forming photons. Ultimately, having gone through four stages of transformation, the nucleon and antinucleon annihilate, turning into photons, neutrinos, and antineutrinos—particles having no rest mass and moving with the velocity of light.

Annihilation occurs because antiparticles, rare guests on earth, are always surrounded by a multitude of particles and annihilate when coming in contact with them. But if antiparticles were isolated in some kind of an antiworld, it would be easy to conjure up different antiatoms, such as antihydrogen consisting of a negatively charged antiproton with a positive electron (positron) rotating about it. The nucleus of antideuterium consists of an antiproton and an antineutron. The nucleus of antitritium contains one antiproton and two antineutrons. One can imagine antioxygen, antiiron, antiuranium, and so on. In an antiworld, all nuclei are charged negatively, and all electrons positively. In our world all stable atoms have the corresponding antiatoms, which are also stable in the antiworld. Outside an antinucleus, an antineutron disintegrates into an antiproton, a positron, and a neutrino. The lifetime of the antineutron is precisely equal to that of the neutron. Any unstable antiparticle lives exactly as long as the corresponding particle does.

From other worlds, it is very difficult to distinguish a world from an antiworld because of the great distance. So far it has not been established whether

our universe contains any antiworlds. The probability of their existence was first pointed out by Dirac in his Nobel lecture as far back as 1933, but until now nobody has been able to spot them. The ingenious Nature has provided means for communication between worlds in the form of photons, which are particles and antiparticles simultaneously. A world and an antiworld emit absolutely identical photons, and it is impossible to establish which of the two emits them. In principle, a world can be distinguished from an antiworld by observing the neutrinos emitted by them. But neutrinos, as well as antineutrinos, are hard to observe because they reluctantly interact with matter. For instance, a neutrino pierces the globe absolutely freely without touching any particles comprising our planet. Therefore a neutrino is very hard to "catch".

Perhaps the most promising method of proving indirectly the existence of antiworlds was suggested by a Soviet scientist Prof. N. A. Vlasov. In an ordinary world, the interstellar gas and gas clouds consist practically only of hydrogen, or proton-electron plasma. In an antiworld, the interstellar gas and gas clouds consist of antihydrogen or antiproton-positron plasma. At the border between a world and an antiworld, protons and antiprotons (as well as electrons and positrons) annihilate when encountering each other. However, they annihilate only on sufficiently close contact. When the distance between them is comparatively great, a proton and an antiproton form a hydrogen-like atom, nucleonium, in which the proton and the antiproton rotate about their common centre of gravity. The spectrum emitted by nucleonium is similar to that of the hydrogen atom, the only difference being that the energy of the photons emitted by nucleonium is as many ti-

mes greater than that of the photons of the hydrogen spectrum as the so-called reduced mass of the proton (antiproton) is greater than the mass of the electron, i.e. 918 times. The reduced mass of the proton in nucleonium is equal to

$$\mu = \frac{m_p m_{\tilde{p}}}{m_p + m_p} = \frac{1}{2} m_p = 918 \text{ em}$$

Nucleonium is formed when the principal quantum number is about 30. The probability of formation of nucleonium is about 10^6 times as high as the probability of annihilation without the formation of nucleonium. Once formed, nucleonium shifts to lower energy levels until the principal quantum number drops to 1 or 2. Then it annihilates.

By registering lines of optical and Roentgen radiation of nucleonium it is possible to find zones in the universe in which antiworlds border with worlds. The main difficulty is that the energy of optical radiation of nucleonium is many times (10^5) less, and the energy of visible and infra-red light, about 10^7 times less than the total annihilation energy of nucleonium. Nucleonium lines will be hardly distinguishable against the general background of radiation emitted from the world-antiworld boundary.

The hypothesis of a universe symmetric relative to matter and antimatter is extremely attractive. A symmetric universe is much richer than an asymmetric one. In the former, matter and antimatter can annihilate and turn into photons and neutrinos, i.e. matter can be born. It is known, for instance, that about 10^{10} years ago the Metagalaxy was in a stage of maximum compression. If the universe is symmetric, it may well be that photons condensed into matter and antimatter, which then separated as the universe expanded. A separation mechanism possible within

one galaxy was proposed by H. Alfven and O. Klein (1963). The mechanism of separation on a greater scale, for instance with one galaxy consisting of matter and another of antimatter, has not been proposed as yet.

At any rate, the search for antiworlds appears to be an extremely intriguing problem.

Writers of science fiction stories often mention photon rockets where matter annihilates with antimatter and turns into photons, which, being reflected from the mirror walls of the photon engine, dash out of the exhaust nozzle and create a thrust necessary for travelling to far-off worlds. These authors disregard the cascade-like nature of the annihilation process. One should take into account not only the fact that comparatively much time elapses before the nucleon-antinucleon pair turns into photons, but also that pi-mesons interact very readily with the rocket material, whereas mu-mesons are extremely inert and will slip out through the engine walls unless some special magnetic traps are built. The neutrinos are carried away from the engine in all directions without setting up a thrust. Thus, the very nature of annihilation greatly affects the design and efficiency of the hypothetical photon engine, to say nothing of the methods of production, accumulation and storage of antimatter, which are very complicated and have not been realized on the required scale (the problems of accumulation and storage have not been solved yet).

Heavy Nuclei

The deuton is the simplest of the complex nuclei, but all other nuclei, no matter how large, also consist of protons and neutrons. The number of protons

determines the charge of the nucleus, and the total number of protons and neutrons, its mass. The helium nucleus contains two protons. Two varieties of helium nuclei—two isotopes—occur in nature. The nucleus of helium-3 contains, in addition to two protons, one more neutron; thus, the total number of nucleons in it is three. The nucleus of helium-4 consists of two protons and two neutrons. Natural helium consists almost entirely of helium-4, its content of helium-3 is only about one-ten-thousandth of one per cent. Carbon nuclei contains six protons and six (C^{12}) or seven (C^{13}) neutrons. The share of carbon-13 in natural carbon is 1.1%, the balance being carbon-12. The most widespread oxygen isotope, oxygen-16, consists of eight protons and eight neutrons. The iron nucleus has 26 protons. Iron has four stable isotopes: 54, 56, 57, and 58. Iron-56 is the most common isotope (91.64%). Gold has only one stable isotope, gold-197, which contains 79 protons and 118 neutrons. The greatest electric charge among the naturally occurring elements is carried by uranium, it is equal to 92. Natural uranium has three isotopes: uranium-234, which is rarely encountered in nature, uranium-235 (0.714%), and uranium-238 (99.28%). In all, today we know 92 naturally occurring elements and about 300 isotopes, part of which are radioactive. There are also twelve man-made elements, from neptunium with an atomic number of 93 to the element 104. Several hundred artificial isotopes have been produced in nuclear reactors and by bombardment of various elements with accelerated protons, deutons, alpha-particles (nuclei of helium-4) and other, heavier particles. All artificial isotopes are radioactive. The total number of isotopes, including natural and man-made ones, exceeds one thousand.

It is well to remember that the volumes of nuclei

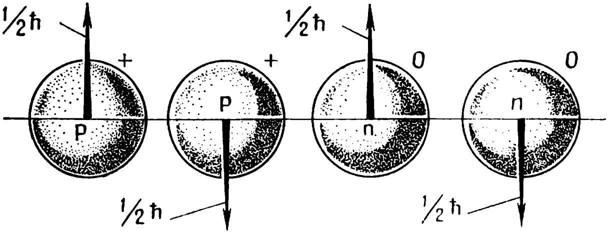

Fig. 16. The nucleus of helium-4 consists of two protons and two neutrons. In each pair the spin is oriented antiparallel, the total spin of the nucleus being zero.

are approximately proportional to the number of nucleons (protons and neutrons) contained in them. The charge of a nucleus is usually denoted by the letter Z; this is the charge (atomic) number of the nucleus. The number of nucleons it contains is given as A, which is its mass number. The number of neutrons in a nucleus is equal to the difference $A—Z$. The volume of a nucleus is approximately equal to that of the nucleon multiplied by the atomic number A. Hence, the radius of the nucleus is equal to that of the nucleon (about 1.3 fermis) multiplied by the cube root of the atomic number.

Until 1911 the scientists had not even suspected the existence of the atomic nucleus. In 1911 the British scientist E.Rutherford discovered that alpha-particles emitted by radium, when passing through a plate of some substance or other, sometimes deviated from their path by a very large angle, as if they stumbled against an electric field concentrated in a very small volume of very large mass. Having counted the number of deviations as related to the total number of alpha-particles, Rutherford estimated the vo-

lume of the atomic nucleus, which proved to be extremely small compared with that of the whole atom.

Naturally, the question of the composition of the nucleus came up. At first it was thought to consist of protons, which determined its mass, and electrons, which compensated part of the electric charge. Some considered, for instance, that the helium nucleus consisted of four protons and two electrons compensating the charges of the two protons. But this was disproved by experimental data. In the first place, the nucleus is so small that the electrons could not possibly squeeze into it.

Imagine that the electron charge is concentrated at some point. We bring an identical point charge to it. In so doing some work has to be done to overcome the electrostatic forces of repulsion. The closer the charges are brought together, the greater is the work and the higher the potential energy of the charges. The distance at which the potential energy becomes equal to the proper energy of the electron, determined by Einstein's formula $E=m_0c^2$, is termed the classical radius of the electron. It is equal to 2.8 fermis, while the radius of the proton (as well as that of the neutron) is equal to 1.3 fermis. If atomic nuclei consisted of protons and electrons, their sizes would be much greater than those found in experiments.

The attempt to construct a model of the atomic nucleus from protons and electrons failed primarily because the electrons could not be packed into the nucleus. Considerations about the size of the nucleus and the electron were, however, not the main argument in rejecting the nucleus model consisting of protons and electrons. This objection could be countered by the assumption that the electrons are compressed when they find their way inside the nucleus.

This assumption, in turn, has vulnerable points, and so on, and so forth. There is a better argument proving that a proton-electron structure of the nucleus is impossible. It may be demonstrated very pictorially using the deuton as an example, although actually it was done with the aid of other nuclei. The deuton was discovered in 1932 after the true structure of the atomic nucleus had been clearly established.

In a nucleus, the spins of its component particles can orient themselves, remaining pairwise parallel or antiparallel. If we assume that it is built up of two protons and one electron, the deuton may have a spin of 3/2, provided that the spins of the three particles are oriented in the same way. When the spins of two particles are antiparallel and compensate each other and the spin of the nucleus is equal to that of the third, uncompensated, particle, the nuclear spin should be equal to 1/2. In actual experiment the spin of the deuton proves to be equal to unity. From this it follows that the deuton cannot be composed of an odd number of particles with a spin of 1/2. A similar contradiction is observed with other nuclei. The proton-electron structure of the nucleus contradicts the principles of quantum mechanics, and it had to be abandoned.

For twenty-one years the physicists knew about the existence of the nucleus, but they did not understand of what building blocks or, more precisely, assemblies it consisted. The solution came in 1932 when the neutron was discovered. Immediately on discovery of the neutron and in the same year a Soviet scientist D. D. Ivanenko, now Professor of Moscow University, suggested that all nuclei consist only of two types of particles, neutrons and protons. Soon after that the hypothesis was developed in detail by the German

physicist W. Heisenberg. At present there is not a single fact contradicting the nucleon structure of the nucleus. In particular, the deuton spin, which is equal to unity, is due to the parallel orientation of the proton and neutron spins in the deuton. The nucleon model was universally accepted. But it was still unclear what forces bind the nucleons inside the nuclei.

Characteristic Dimensions of Particles

In the preceding section we gave one of the characteristic dimensions of the electron, its classical radius. Recall that the classical radius r_0 is equal to the distance at which the electrostatic energy of interaction of an electron with a point charge of the same size is equal to the proper energy of the electron:

$$\frac{e^2}{r_0} = mc^2$$

where e is the electron charge. Hence we have

$$r_0 = \frac{e^2}{mc^2} \qquad (4)$$

No reference book gives the classical radius of the proton or the neutron. The reason is that the classical radius of these particles is negligibly small as compared with the true radius, which is determined by the nuclear forces, these have a different origin than the electromagnetic forces acting between electrons.

Each elementary particle has several characteristic dimensions. They include the Compton wavelength of a particle.

The energy of an emission quantum is equal to the product of the quantum of action h by the frequency of electromagnetic oscillations

$$E=h\nu$$

The frequency is, in turn, equal to the light velocity divided by the wavelength of the photon:

$$\nu=\frac{c}{\lambda}$$

The wavelength of such electromagnetic oscillations, whose energy is equal to the proper energy of the particle, is termed the Compton wavelength. The conditions for the equality of energies can be written thus:

$$h\nu=h\frac{c}{\lambda}=mc^2$$

whence

$$\lambda=\frac{h}{mc} \tag{5}$$

The Compton wavelength characterizes the magnitude of the proper energy of a particle. For the electron this length is 2.4×10^{-10} cm, for the proton, $1.3\times\times10^{-13}$ cm (1.3 fermis). Sometimes, in order to calculate the Compton wavelength use is made of the quantum of action $\hbar$ which is 2π times less than h. Then the Compton wavelength is denoted by $\lambda\!\!\!^{-}$

$$\lambda\!\!\!^{-}=\frac{\hbar}{mc} \tag{6}$$

For the electron, $\lambda\!\!\!^{-}=3.8\times10^{-11}$ cm, and for the proton, 0.2 fermi.

Each particle in the microworld simultaneously possesses corpuscular and wave properties. An electron beam passing through a crystal behaves like light

(electromagnetic waves). The electrons, flowing around the atoms of the crystal lattice and merging together in the passing beam, yield maxima at points where the propagation difference is a multiple of an integral number of wavelengths characteristic of electrons, and minima where it is a multiple of an integral number of half-wavelengths. This phenomenon is called diffraction, it is typical of waves and is used for determining the dimensions of a crystal lattice. The wave properties of the electron and proton are used in electron and proton microscopes.

A hypothesis of the wave properties of matter, which was later brilliantly confirmed and served as one of the foundation blocks of quantum mechanics, was proposed in 1924 by the French theoretical physicist Louis de Broglie. Therefore the wave of matter is referred to as the de Broglie wave. The length of this wave is inversely proportional to the kinetic energy of the particle, more precisely, to its impulse:

$$\lambda = \frac{h}{mv} = \frac{h}{p} \tag{7}$$

For an electron of energy 1 MeV it is equal to 1.2×10^{-11} cm, for a 1-GeV electron, 1.2×10^{-14} cm.

The de Broglie wavelength does not characterize any inherent properties of a particle; it characterizes its impulse determining its wave properties. Here we speak of it because of its exceptional part in the microworld.

The smallest particle dimension which we will encounter below (with one exception) is the gravitation radius. All particles are attracted to each other by the force of gravity. The closer two particles are to each other, the greater is the force of attraction between them, and the work which has to be done to separate the particles by a distance such that the

force of attraction can be neglected. The distance at which the gravitational energy is equal to the proper energy of the particle is called its gravitation radius. In the gravitation field theory, the conventionally adopted gravitation radius is twice as large.

The equality of the gravitation and proper energies is expressed thus

$$G\frac{mm}{r_0} = mc^2 \tag{8}$$

where G is the gravitation constant equal to $6.67 \times \times 10^{-8}$ cm^{3}g^{-1}s^{-2}. Hence, the double value of r_0, or the length of the gravitation radius of a particle, is

$$R = 2r_0 = \frac{2Gm}{c^2} \tag{9}$$

The gravitation radius of the electron is 1.35×10^{-15} cm, for the proton it is 1836 times as large. The gravitation radius of the sun is about 3 km. Sometimes a halved value (1.5 km) is given. The factor 2 in equation (9) is then neglected.

Gravitational forces in the microworld are negligibly small compared with electromagnetic and, of course, nuclear forces. The gravitational energy is also negligibly small. The value of the gravitation radius of microparticles is given solely as illustration. Available data show that it is small as compared with the other characteristic dimensions, such as the Compton wavelength.

The gravitation radius of the sun (3 km) is very small compared with its geometric radius (695 500 km), which also points to a small relative value of the sun's gravitational energy in comparison with its proper energy. In 1962-3 so-called superstars were discovered, which are now being intensively studied. It is presumed that their mass is of the order of 10^5

to 10^8 solar masses, i.e. the mass of an entire galaxy (the mass of the sun is 2×10^{33} g). The principal source of energy of superstars which causes their light and radio emission is probably the gravitational energy. When the gravitation radius of a body (only space objects are implied, of course) is equal to its geometric radius, the body acquires interesting properties, in particular, it does not emit any radiation.

Nuclear Forces. Pi-Mesons (Pions)

The main distinguishing feature of the nuclear forces (this became clear after very refined and ingenious investigations requiring tremendous efforts) is their extremely small range. Nuclear forces, which are very strong at short distances, disappear at distances of a few fermis. It is generally accepted that their range is 1.4 fermis. Their second important property is that they are practically independent of the particle charge. Thus, nuclear forces between two protons are the same as between two neutrons. The forces operating between protons include also electrostatic forces of repulsion, which do not operate between neutrons. But we are not concerned with these here; we have in mind specific nuclear forces.

Nuclear forces, i.e. interaction between nucleons, are studied in the process of scattering of nucleons from nucleons. By directing a beam of protons or neutrons at a hydrogen target (protons) and thoroughly investigating the deviation of the flying particles from their original direction, scientists study the forces acting between proton and proton and between proton and neutron. The forces operating between

two neutrons cannot be determined directly, because it is impossible to prepare a target from neutrons alone. Therefore researchers use targets of deuterium, whose nucleus contains a proton and a neutron. The forces operating between neutrons are determined from the difference between the interaction of neutrons with protons and neutrons with deutons.

The Soviet scientists Academician I. Tamm, Nobel Prize winner, and Professor Ivanenko were the first to describe nuclear forces as exchange forces. Exchange forces are a specific quantum-mechanical concept which has no analogy in ordinary life. Two particles are bound together with the aid of a third particle, which they exchange continuously. Tamm and Ivanenko showed that nuclear forces could not be attributed to electrons and neutrinos, particles known at the time (1934). In the next year a young Japanese scientist H. Yukawa suggested that nuclear exchange forces are due to a new, then unknown particle, the meson with a mass of about 200 em. According to Yukawa, the mean range of nuclear forces [a distance at which they reduce by a factor of e (2.7)] is equal to $\hbar/mc$. This is the Compton wavelength of a particle exchanged by two nucleons The range of nuclear forces is known from experiment; it is equal to about 1.4 fermis. Assuming that $\hbar/mc$ is equal to 1.4×10^{-13}, it is possible to determine the mass, since $\hbar$ and c are known:

$$m=\frac{10^{-27}}{3\times10^{10}\times1\cdot4\times10^{-13}}\simeq2\cdot5\times10^{-25}$$

Dividing the obtained figure by the electron mass equal to 9.1×10^{-28} g, we find the mass of the hypothetic Yukawa particle in em. It is equal to 275 em. At first Yukawa obtained the figure 206 em, since he used a slightly greater range of nuclear forces.

Naturally, experimenters began an intensive search for the meson. The next year, Anderson and Neddermeyer (USA) found a particle of mass 207 em (mu-meson) in cosmic rays. But the mu-meson has nothing to do with nuclear forces. The fact that the mu-meson was found in the lower layers of the atmosphere also seemed rather strange. This circumstance alone pointed to its weak interaction with matter: a mu-meson passes from the upper layers of the atmosphere to the lower ones and is not absorbed by the nuclei of atmospheric nitrogen or oxygen. Later on, direct experiments showed that mu-mesons practically do not interact with nuclear matter and therefore are in no way related to nuclear forces. The particle binding nuclei together should be readily "attracted" to the nuclei and should eagerly interact with them. It was not before 1947 that a lengthy and persistent search had lead to the discovery of the true binding links between nuclei—pi-mesons. They were also found in cosmic rays, but in the upper layers of the atmosphere. Forming at a great altitude on interaction of cosmic rays with the nuclei of the gases comprising the air, pi-mesons rapidly disintegrate or are absorbed by nuclei and do not reach the lower layers. Only mu-mesons, products of disintegration of pi-mesons, reach the earth.

A proton and a neutron exchange a charged pi-meson. A proton and a neutron interact, exchanging also neutral pi-mesons, but they do not transform into each other. The proton, losing a plus pi-meson to the neutron, turns into a neutron. Then the process is reversed. The proton and the neutron continuously transform into each other. One can conjure up an interaction with the aid of a negative pi-meson as well. A neutron, emitting a negative pi-meson, turns into a proton. A proton takes on a negative pi-meson,

which neutralizes the proton charge, and turns into a neutron, and so on. But two identical nucleons—a proton and a proton or a neutron and a neutron—cannot exchange a charged pi-meson. If a proton gives up its positive charge to another proton, the second proton will carry two positive charges and will cease to be a nucleon. A proton cannot give up a negative charge either, since in that case it would be left with two positive charges. A neutron which has given up a positive charge to another neutron acquires a negative charge. But there are no negative neutrons (the antiproton has a negative charge, but it is an antiparticle the production of which requires a very high energy; it cannot be obtained by adding a pi-meson to a nucleon), and such a process is impossible. A neutron cannot give up a negative charge either, since another neutron ceases to be a nucleon on receiving a negative charge. A proton exchanges a neutral pi-meson with another proton, and so does a neutron with another neutron*. A neutral pi-meson strongly interacting with nuclei of matter does exist in nature, otherwise the exchange scheme would be much more intricate. To eliminate the above contradictions arising during the exchange of a charged particle between a proton and another proton or between a neutron and another neutron, one would have to presume that identical nucleons exchange *two* particles simultaneously. For instance, when a proton gives up a positively charged particle to another proton, it simultaneously receives an identical meson from the other proton.

So far we have freely transferred a pi-meson from one nucleon to another. The mass of a charged pi-

* If a Δ-baryon were born in the nucleus (see page 246), this meson could be charged.

meson, as determined experimentally, is equal to 273 em, and that of a neutral one, 264 em. As a result, one nucleon becomes "lighter" than a usual (non-interacting) one, the other becomes "heavier" until it returns the borrowed pi-meson to the first nucleon. But the nucleon has a strictly defined mass which cannot be reduced. What is then the source of energy and mass of the pi-meson emitted by the nucleon? Doesn't this contradict the law of conservation of energy?

Uncertainty Relation and Virtual Processes

In 1927 Heisenberg, one of the founders of quantum mechanics, formulated the famous uncertainty relation, which has received, as well as quantum mechanics in general, very wide recognition.

The uncertainty relation has the form

$$\Delta p \Delta x \geqslant \hbar \qquad (10)$$

where Δp is the uncertainty in the value of the particle impulse, and Δx, the uncertainty in its coordinate. It is impossible to know precisely the coordinate and impulse of a particle simultaneously [see equation (10)]. The more accurately one of these values is given or determined, the less accurate is the other one. The problem does not lie here in the efficiency of the equipment or of the measuring procedure, the uncertainty relation reflects the substance of phenomena occurring in the microworld.

In the microworld, each particle possesses not only corpuscular but also wave properties. It is not only

a particle but also a package of waves, or a wave of length

$$\lambda = \frac{h}{p}$$

Some experiments reveal the corpuscular properties of particles, and others (for instance, experiments with particle diffraction), their wave properties. If the particle impulse is given (it can be set by accelerating the particle to a definite velocity in an accelerator), then, according to equation (7), the de Broglie wavelength is also known. Clearly, the particle size cannot be less than the wavelength. The position of a particle cannot be marked as a geometric point, the uncertainty in the position will be not less than the wavelength. From this it follows that the particle impulse and coordinates cannot be found simultaneously and precisely. This can be done only approximately, with a certain uncertainty.

The magnitude of this uncertainty is found strictly mathematically, but it can be deduced from dimensionality considerations. The product of impulse by length or of impulse uncertainty by length uncertainty has the dimensionality of action. In the microworld, action is quantized, the magnitude of a quantum of action cannot be less than $\hbar$ because the latter magnitude is associated with the minimal known value of the dimensionality of action by which the particle orbital momentum or spin can change, for instance the spin of electron and of other fermions.

A quantum of action cannot be split into smaller magnitudes. Hence it may be inferred that the magnitude of action dimensionality, i.e. the product of impulse indeterminacy by coordinate indeterminacy, cannot be split either, it should be equal to $\hbar$ or greater, but by no means less. If it were less, a quantum

of action less than $\hbar$ would appear in nature. There would be cases where a spin or orbital momentum would change by a value less than $\hbar$.

As has already been said, the dimensionality of action is assigned to still another magnitude, i.e. the product of energy by time. Therefore the uncertainty relation can also be written as

$$\Delta E \, \Delta t \geqslant \hbar \tag{11}$$

In contrast to the uncertainty in the coordinate Δx in equation (10), here Δt does not mean uncertainty in time. The magnitude Δt is the lifetime of a state whose energy is being measured. The greater this lifetime, the more accurately the energy is determined and the less is its uncertainty ΔE. Consequently, if we wanted to measure the energy of a state with a zero lifetime, we would obtain energy uncertainty equal to infinity. In this case the particle energy cannot be estimated.

On the other hand, when the lifetime of a state is sufficiently long, for instance, a whole second, the energy can be determined with a tremendous accuracy, in this case up to 1×10^{-27} erg. And conversely, when the energy of some state is indeterminate in value, it can be asserted then that the lifetime of this state is equal to the quantum of action divided by the uncertainty in energy.

Using the uncertainty relation one can calculate the lifetime of a particle state if it is too small to be measured by other methods. The proper energy of a particle is proportional to its mass (mc^2), therefore the particle mass is often determined in megaelectronvolts, here, the concept of proper energy and not of mass is used. The mass of the omega-zero-particle is equal to 783 MeV (1533 em), the mass (energy) uncer-

tainty being about 7 MeV. This is not an error in mass measurement; simply, each time determinations yield different figures, and the mean energy spread is 7 MeV. The lifetime of the omega-particle is found as a ratio of the quantum of action to the uncertainty in the proper energy of the particle; it is equal to $\hbar/7$ MeV, i.e. about 5×10^{-23} sec.

Similarly, the lifetime of an excited state of a nucleus is estimated from the width of the line of gamma radiation emitted by the nucleus. The width of gamma lines (their spread) is always very small, therefore the lifetime is rather long as compared with the nuclear lifetime.

In everyday life, where the lifetimes of states are rather large, energy uncertainties are extremely small. But in the microworld, where the distances between particles are very small and the velocities are great (close to the light velocity), the lifetimes of different states may be quite small, and the uncertainty relation should not be neglected.

An uncertainty relation of the type (10)—the product of uncertainty in impulse by uncertainty in coordinate—differs considerably from a relation of the type (11). This is due to the difference in the mathematical properties of the so-called operators, which describe the impulse and coordinate in one case and the energy and time in the other. As was noted above, the difference consists in the fact that in the first case use is made of *uncertainty* in the coordinate, and in the second, of the state's lifetime on which the energy uncertainty depends.

A very interesting conclusion can be drawn from the uncertainty relation. It appears that referring to the microworld it is impossible, in principle, to speak of a simultaneous and strictly defined value of the kinetic and potential energy of a particle. For ins-

tance, assume that a particle is inside an atomic nucleus and moves with a certain velocity relative to some reference points. Its kinetic energy is equal to the square of the impulse divided by the doubled mass, $p^2/2m$. The potential energy is independent of the velocity, it depends on the position of the particle relative to the other particles, i.e. on its coordinate. The impulse and the coordinate, however, cannot be known accurately at the same time, because the uncertainties in their values are related by the uncertainty relation (10). Consequently, there is no accurate value of the kinetic and potential energy of a particle simultaneously, the former depending on the impulse and the latter, on the coordinate. If the kinetic energy is known very accurately, there is a considerable uncertainty in the potential energy. Incidentally, this circumstance is extremely important for the understanding of radioactive alpha-disintegration of atomic nuclei.

Various arguments concerning the uncertainty relation have been put forward. Idealistically minded scientists spoke of "limits of cognition" of matter. But this is not the point. Approached philosophically, the uncertainty relation is profoundly materialistic. Evidently, it reflects the philosophical premise that matter exists in space and time. If we consider it disregarding space (the length is equal to zero) and time (the time is equal to zero), we arrive at absurd results: the particle impulse and energy are equal to infinity.

We will now use the uncertainty relation in describing intranuclear phenomena. If observed sufficiently long, the mass of a nucleon, say a proton, will prove to be 1836 em. The corresponding energy is equal to the product of the mass and the square of the light velocity. But if the time interval is small,

the particle energy, and hence its mass, cannot be determined accurately, since there is simply no accurate value. Thus, the mass may exceed the given value (1836 em) for a short time, and the shorter the time, the greater the excess. Using the uncertainty relation (11) one can find the period in which the uncertainty in energy will become equal to the energy required for the formation of a pi-meson. To find this period, $\hbar$ must be divided by the pi-meson mass multiplied by the square of the light velocity. As a result we obtain about 4.7×10^{-24} sec. Within this time the uncertainty in the nucleon energy is equal to the proper energy of the pi-meson, and the uncertainty in the nucleon mass, to the mass of the pi-meson. During this period the nucleon can give up the pi-meson and regain it. In this case the law of conservation of energy is not violated. Energy is borrowed for a short time from internal sources as it were.

This process is called virtual, i.e. acting, equivalent, causing effects.

Thus, a virtual pi-meson appears for about 4.7×10^{-24} sec, this is its lifetime. How far can it travel within this time? For a distance which does not exceed the product of this time by the light velocity. Multiplying 4.7×10^{-24} sec by 3×10^{10} cm/s, we obtain 1.4×10^{-13} cm. This is the range of nuclear forces, we have obtained it from the mass of the pi-meson and the uncertainty relation. Here we actually use the same arguments as were used when describing Yukawa's idea. The distance of 1.4 fermis has been obtained from the mass of the pi-meson. Formerly we performed a similar operation, specifying the distance from which the meson mass was found. The figures differ somewhat, because the preliminary estimate of the meson mass yielded a lower value (206 em)

as compared with the actual mass of the pi-meson (273 and 264 em).

Considering exchange nuclear forces, it is useful to recall the elementary principles of quantum mechanics. The uncertainty principle shows that the law of conservation of energy cannot be violated in the exchange of a pion between two nucleons. But this principle also indicates that the exchange is not so simple as described above. Indeed, it is too primitive to say that one nucleon gives birth to a pi-meson at a certain instant and then the pi-meson covers the distance between the nucleons (which takes about 10^{-24} sec) and is absorbed by the other nucleon, whereupon the process is reversed.

When we say "at first the pi-meson was born", we assert that it was born within a time less than 10^{-24} sec. But the uncertainty in the pi-meson energy will be much greater here than its proper energy (m_0c^2). Therefore the breakdown of the "exchange" process into stages in time and consideration of the movement of the pi-meson from one nucleon to the other has no sense. If we recall the principle of superposition of states, it will immediately become clear that the concept of alternate transitions of the nucleon from the proton to the neutron state and back is wrong. If the proton and the neutron are bound to each other, there is always the probability that the proton is simultaneously a neutron and the neutron is a proton.

But, since particles do exchange properties, this exchange is better represented as certain material currents in nuclear matter. These currents are short-lived, they are a kind of eddies comparable with the nucleon in size. Speaking rigorously, however, this is wrong too, any pictorial representation in the description of exchange nuclear forces, as well as of other phenomena inside the nuclear matter, will be very

far from reality in the world of large bodies which we perceive with our five senses. By studying the microworld and constructing mathematical models of events taking place in the microworld scientists find those macroscopic effects, those consequences which stem from microworld events. These are verified by experiment. The process of cognition of the microworld includes, as a necessary step, logical generalization (abstraction) and mathematical formulation. It consists roughly of the following stages: observation of phenomena which cannot be described with the aid of classical theory, quantum-mechanical statement of the problem, solution of the quantum-mechanical problem, conclusions from the solution as to the macroscopic effects of micro-events, and also observation of expected results in experiment and comparing them with theoretical predictions.

Nuclear Forces (Continued)*

Considerations concerning the exchange nature of nuclear forces give only an approximate idea of the forces actually operating between nucleons. Experiment points to a more complex nature of the forces. According to physicists, exchange forces operate over comparatively large distances (1-1.5 fermis) between the centres of nuclei. If we consider the whole range of distances between nucleons, we will see that at least two or three types of forces operate there which differ not only in magnitude but also in the nature of their action.

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* See the beginning on page 67.

Physicists usually avoid the concept of force in this connection, they estimate interaction between particles in terms of energy. If one particle is attracted by another, separation of particles requires an energy equal to the product of the force by the distance by which the particles are to be separated. But the force rapidly reduces with distance. Therefore the force cannot be simply multiplied by the overall distance; the force will be different for different portions of the distance. Therefore the distance between the particles is divided into sections for which the force may be considered constant. Naturally, the force changes from one section to another. For each section the force is multiplied by the distance, and all the products are summed up; this is called integration. In actuality it is more convenient to bring particles together than to separate them. Then, if the energy of the separated particles is taken to be zero, when they are brought closer together, the potential energy reduces, just as it does when a body falls to earth. But we took the initial potential energy to be zero and therefore, as the particles are attracted to each other (approach each other), the potential energy becomes negative. The faster it reduces with decreasing distance, the greater is the force of attraction between the particles. If the potential energy begins to increase as the particles continue to approach each other, forces of mutual repulsion arise.

Calculating the mean distance between the particles in the atomic nucleus and knowing how the potential energy changes with distance, one can find the energy released when the nucleons approach each other by a given distance. This energy is equal to the binding energy of the particles in the nucleus. To remove a particle from the nucleus an amount of energy equal to the binding energy has to be spent. When a particle

penetrates into the nucleus the binding energy at first transforms into the kinetic energy of the particle, then into the excitation energy of the nucleus and after some time is emitted from the nucleus as gamma quanta (photons). The photons, carrying energy away from the nucleus, also carry away a mass equal to the energy divided by the square of the light velocity. Thus, the mass of the nucleus becomes less than the sum of the masses of the nucleons of which it consists. This difference in masses is called the mass defect. The closer the nuclei are to each other, the tighter they are "packed", the greater is the mass defect. The mass defect characterizes the "packing" of nucleons in nuclei, therefore it is sometimes called packing or the packing factor.*

Let us, however, return to the nuclear forces. As has already been said, they are very strong and operate over short distances. The prominent researcher into nuclear forces R.Marshak says that nuclear forces operating over a distance of 1 fermi are 35 times greater than electrostatic forces and 10^{38} times greater

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* Strictly speaking, the mass defect is the difference between the mass of the nucleus and the mass number A. The packing factor is a ratio of the mass defect to the mass number. According to this definition even the neutron—an elementary particle—has a mass defect of 8.98×10^{-3} amu (atomic mass units). The atomic mass unit is equal to 1/16 of the mass of the atom of oxygen, O^{16}. The definition given in the text is not so strict, but it has a physical meaning. Since 1960 scientists of many countries have been using the unified atomic mass unit equal to 1/12 of the mass of the atom of carbon C^{12}. The ratio of the old unit to the new one is equal to

$$\frac{\text{mass in physical scale } (O^{16}=16)}{\text{mass in unified scale } (C^{12}=12)} = 1.000317917 \pm 0.000000017.$$

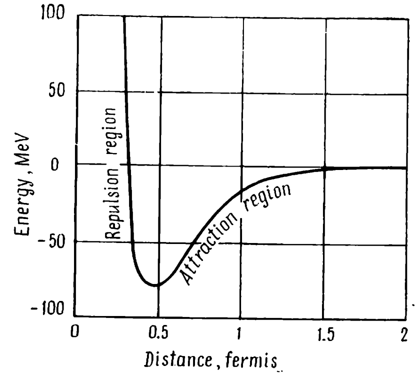

Fig. 17. Variation in potential energy as two protons with antiparallel spins approach each other.

than gravitational forces. Experimental investigations of forces or, which is the same, of potential energies, indicate such a great complexity of forces and their dependence on several factors that they cannot be described by any single mechanism. It cannot be said definitely whether the Yukawa hypothesis is true, although it is, indeed, very attractive and productive (an example is the discovery of two types of mesons).

As has been mentioned above, nucleus possesses an angular momentum (spin), which is the same for the proton and the neutron and which is equal to $1/2\ \hbar$ for each of the particles. When two nucleons, say a neutron and a proton, approach each other, their spins may, according to quantum mechanics, assume a parallel or antiparallel orientation. In the former case the total spin of a system of two particles is equal to unity. This is how they are oriented in the deuton, the nucleus of deuterium. With antiparallel orientation the total spin of two particles is zero. Then the

pair of particles, as a whole, has no characteristic direction, all directions in space are the same for it. In this case only so-called central forces operate between the two particles. The central forces are directed along a straight line between the interacting particles and are independent of their orientation in space. Examples are electrostatic and gravitational forces. Central nuclear forces are also independent of the spatial orientation of the interacting nucleons. But central nuclear forces naturally differ from electrostatic and gravitational forces as regards their magnitude and the law of their reduction with distance.

The existence of a deuton with a unit spin and the absence of a deuton with a zero spin (there is no deuton with oppositely directed neutron and proton spins) indicates that a proton and a neutron are bound to each other much stronger with parallel than with antiparallel spins. This points to the existence of so-called spin forces. Generally, spin forces operate between any nucleons.

If two nucleons, say two protons, have an orbital momentum (for this to happen, one of the protons should fly rapidly enough past the other), the magnitude and direction of the spin forces depend on the mutual orientation of the total spin relative to the orbital momentum. Let us dwell on this in more detail.

Suppose that when we bombard target protons with protons accelerated in a cyclotron, two protons approach each other with their spins parallel and the total spin equal to unity (it has a definite direction in space). For this direction to acquire a certain meaning, a reference direction is necessary, i.e. the direction relative to which the total spin of the pair can be oriented. This can be the orbital angular momentum. If one proton approaches another and finds itself in the field of nuclear forces, its path curves in and the

proton winds around the other proton. Since the masses of the two particles are comparable, the other proton also deviates, and they both begin to rotate about their common centre of gravity. True, they do not make a complete revolution, since the impinging proton flies on after deviating from its path. And still, at the moment of rotation about the common centre of gravity there arises an angular momentum equal to the product of the proton mass by its velocity and by the distance from the proton to the centre about which it is rotating. The orbital momentum has the direction in which a right-handed screw advances turning with the proton. There is also another method of determining the direction. If the middle finger of your right hand points away from a flying proton to the centre about which it is rotating, the index finger points in the direction of the particle, then the thumb, pointing perpendicular to the index, will indicate the direction of the orbital angular momentum.

After familiarizing oneself with the structure of the hydrogen atom one will readily understand that the orbital angular momentum of two nuclear particles is also quantized, as is the orbital electron momentum in the hydrogen atom. It can assume values equal to 0, 1, 2, 3, and so on (in terms of $\hbar$). The respective states are termed, as in the atom, the S-state ($L=0$), P-state ($L=1$), D-state ($L=2$), etc. The capital letters are used here evidently because the nucleus is more solid than the atomic shell.

It has been found experimentally that the spin component of nuclear forces depends on the orientation of the spin momentum relative to the orbital momentum. But the spin momentum, with the spins parallel, is equal to unity, any one of its components (in this case, the one along the orbital momentum) can only take one of three values—for the parallel,

perpendicular, and antiparallel positions. Each of these values differs by unity from the preceding one. If the spin momentum is parallel to the orbital momentum, then two protons with parallel spins are weakly attracted to each other, with a perpendicular orientation they repulse each other, and with an antiparallel orientation they strongly attract each other.

The nucleons in the deuton have no orbital momentum. But the deuton has a so-called quadrupole electric moment. The spin forces in the deuton depend on the orientation of the spin relative to the direction of this moment.

It should be noted that with a parallel direction of the spins of two colliding protons (or neutrons) the orbital momentum can assume only odd values: 1, 3, and so on; with an antiparallel direction, only even ones: 0, 2, 4, etc. This is a kind of manifestation of the "individualism" of fermions (particles with spins of $^1/_2$), which is expressed by the Pauli principle for nucleons flying past each other.

In addition to forces arising due to spin interaction there is one more type of force whose magnitude and direction depend on the orientation of a pair of particles with parallel spins; these are spin-orbital forces. Spin-orbital forces are non-existent when the spins of two particles are antiparallel and their sum is equal to zero. This is a trivial fact: no spin, no spin-orbital forces.

With a parallel orientation of the spin relative to the orbital momentum there are relatively small forces of attraction acting in the same direction as the spin forces; with a perpendicular arrangement there are relatively weak forces of repulsion (here their direction also coincides with that of the spin forces); with an antiparallel arrangement there appear forces of repulsion between the particles (with this orientation the spin forces have opposite signs).

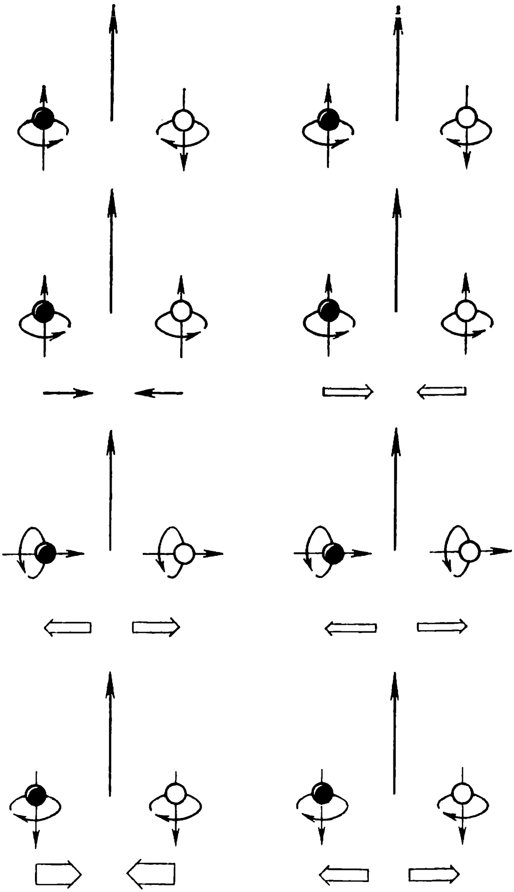

Fig. 18. Spin (left) and spin-orbital (right) forces between nucleons exist only with a parallel arrangement of the spins of the interacting nucleons, i.e. with a non-zero total spin of the nucleons. In the figure, the thickness of the horizontal arrows is proportional to the force. The arrows piercing particles indicate the direction of the spins, the long vertical arrows, the direction of the orbital momenta (see *Scientific American* No. 3, 1960).

Spin-orbital forces differ from spin forces in that they depend (somewhat differently than the spin forces) not only on the mutual positions of the spin and the orbital momentum but also on the magnitude of the orbital momentum. They are more pronounced at high energies, at greater orbital momenta of two interacting nucleons.

Spin and spin-orbital forces act over slightly larger distances than central forces. Central forces between two protons, at any rate over distances of 0.5 to 1 fermi, also vary with distance to a different extent, depending on whether the particle spins are parallel or antiparallel.

We have dwelt at some length on the description of forces in order to show how complicated this problem is in reality and how far the physicists are from a complete understanding of nuclear forces. At the same time this brief description shows how far ahead they have moved along this path. Forces are now measured over distances less than 10^{-13} cm, and scientists investigate such intricate phenomena as the effect of orientation of nuclear spins relative to each other and to the orbital momentum. In this connection it will be appropriate to say a few words on the methods for investigating nuclear forces or, more precisely, the potential energies of nuclear particles, in the course of their interaction.

To investigate interaction of two nucleons, protons are accelerated to energies exceeding 100-200 MeV. The potential energy of interaction over distances of 0.5 to 0.7 fermi may be as high as 100-200 MeV*. To prevent the sticking of a particle in the nucleus

* The first substantial information on nuclear forces (their range and other data) was obtained at energies below 20 MeV.

and give it a chance to go on after colliding with another particle and scattering from the target, a store of energy is required. But this is not all. There is another factor determining the magnitude of the necessary kinetic energy of the impinging particle. We want to obtain orbital momenta of different values upon collision (this is needed for measuring spin-orbital forces). But the orbital momentum cannot take on an arbitrary value. In the first place, it is quantized and is expressed as $L\hbar$. The orbital momentum is equal to the product of the mass of the flying particle by its velocity and by the distance by which the particles approach each other ($L\hbar = mvd$) or, more accurately, by half this distance, because the particles rotate about their common centre of gravity situated half-way between them. But the mass has been specified, the distance d is also limited, it cannot exceed the range of the nuclear forces, since over large distances there are no forces, there is no interaction, and the particles will not scatter. Consequently, the only way to obtain an increased orbital quantum number L is to augment the particle velocity, i.e. its energy. Let us find, for instance, the minimum velocity (and minimum kinetic energy) of an impinging particle required for reaching the D-state (orbital number $L=2$). The particle velocity, neglecting the relativistic effects (following from Einstein's theory of relativity), is equal to $v=2\hbar/md$, and the kinetic energy $E=mv^2/2=$ $=2\hbar^2md^2$. Substituting the values of $\hbar$ and m with due regard for the fact that the range of nuclear forces is 1.4×10^{-13} cm, and converting the figure obtained into megaelectron-volts (dividing it by 1.6×10^{-6}), we find that $E=45$ MeV. For a doubled quantum number the energy should be four times as high, about 180 MeV. Our primitive calculation greatly underrates the energy. In actuality both figures are much higher.

But energy cannot increase indefinitely. At about 300 MeV a collision of nucleons gives rise to pi-mesons, and the whole picture of scattering, which is very complex as it is, becomes completely confused. Energies higher than 300 MeV refer to physics of elementary particles rather than to nuclear physics.

It is not yet clear what the highest energies associated with elementary particles are. In any case the existing accelerator for proton energies up to about 50-70 GeV is a far cry from those of which the physicists are dreaming. Particles of energies up to 10^{10} GeV occur in nature. This is two hundred million times as high as the energy of particles which will be obtained on the 70-GeV accelerator. We will need new technological ideas, tremendous energy sources and, of course, time for laboratory-scale reproduction of naturally occurring phenomena. In future, accelerators with counter-beams will probably be built. Then it will be possible to obtain very high relative energies. But such accelerators will need very high particle flux densities. In rarefied fluxes particles will collide very seldom.

At proton energies of about 100-200 MeV a particle beam impinging on a target and scattering from it contains particles which have been in a state with the maximal orbital quantum number, but with smaller numbers as well. In a scattered beam, the *S*-, *P*- and *D*-states are superimposed on each other up to the maximum state possible according to the orbital momentum. Experts say that treatment of experimental data is extremely difficult, it requires an exceedingly rich theoretical background.

Investigations of interactions between nucleons have been greatly promoted by the discovery of the polarization of a proton beam when passing through a target consisting of protons. This discovery was made

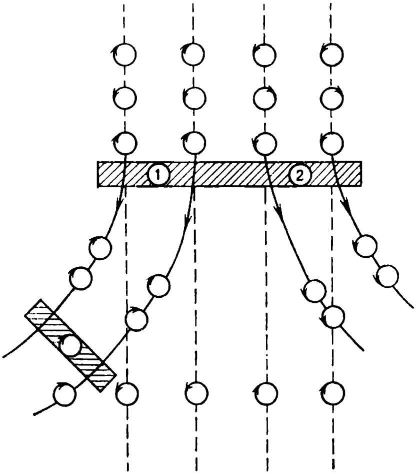

Fig. 19. Nucleon polarization on scattering. Nucleons whose spins are antiparallel to those of the target fly largely in a straight line due to the absence of spin-orbital forces. Nucleons with parallel spins deviate to right and left. Each of the deflected beams is polarized, it consists of nucleons with identically oriented spins. The spins of the nucleons deflected to the left are directed away from us, those of nucleons deflected to the right, towards us. On encountering the second target the beam becomes still "purer", the relative fraction of nucleons deflected to the left is larger than it was after encountering the first target.

in 1953 by R.Oksley at Rochester University. Let us draw (Fig. 19) two protons of a target: proton *1* rotating clockwise with its spin directed away from us, and proton *2* rotating counterclockwise, its spin being directed toward us. Flying protons can only have spins oriented parallel or antiparallel relative to the target protons, any other possibilities are excluded.

Protons with antiparallel spins experience neither spin forces nor spin-orbital forces, and therefore we do not draw them. Above proton *1* we draw two flying protons with spins oriented as that of proton *1*; over proton *2* we have two flying protons rotating with proton *2*. The orbital momentum of the pair consisting of proton *1* and the particle flying to the right of it is directed away from us, as well as the total spin of the two protons. Therefore the flying proton is attracted to proton *1*. The proton flying to the left of proton *1* sets up an orbital momentum directed toward us, i.e. opposite to the spin. The spin-orbital force repulses it from proton *1*, and the left-hand proton, as well as the right-hand one, turns to the left. All protons whose spins are directed away from us are deflected to the left by the target protons rotating clockwise. If we consider proton *2* rotating counterclockwise in a similar way we see that flying protons with spins parallel to that of proton *2* deviate to the right. Antiparallel protons fly past the target protons along a straight line, or, more precisely, are attracted to proton *2* (as well as *1*) on both sides. The degree of polarization can be determined by placing another target in the path of a polarized beam, for instance the one deflected to the left. The beam which deviates to the left on encountering the second target contains more polarized protons deflected to the left than the first one, it has more particles with clockwise spins. Still more uniformity can be attained by interposing a third target. By calculating the number of particles deflected one way or the other after hitting each of the targets and measuring the angles of deviation for beams with flying protons of different energies, one can obtain very valuable data for determining nuclear forces, especially spin- and spin-orbital ones. It is easy to write about experiments,

but in practical work they require much labour, money and time, sometimes many years.

In conclusion we will sum up the information on nuclear forces. One of their most interesting properties, in addition to a great magnitude and a short range, is their charge independence. Nuclear forces operating between two protons are exactly the same as those between neutrons. Forces between a neutron and a proton practically do not differ from those between two protons and between two neutrons. There may, however, be a slight difference. The point is that on collision of two identical nucleons, the orbital momentum may, according to the Pauli principle, take on even values (0, 2, 4, ...) if the nucleon spins are antiparallel, and odd values (1, 3, 5,...) if they are parallel. Therefore, for antiparallel spins the S-state ($L=0$) is possible according to the orbital momentum. This state has no preferred direction (both the orbital and total spin momenta are equal to zero), on passing particles at rest, incident particles scatter equally in all directions. The scattering is characterized by spherical symmetry. For the case of parallel spins the lowest is the P-state with a unit orbital momentum and spin.

None of these considerations is applicable in studying interaction between a proton and a neutron (or a neutron and a proton). This is attributed to the fact that the proton and the neutron are different particles, and the Pauli principle is inapplicable to such a pair. For this reason all states characterized by a complete spectrum of orbital momenta ($L=0, 1, 2, 3, 4,...$) are possible both for a parallel and an antiparallel arrangement of spins of two colliding particles. This circumstance affects the forces of interaction between a proton and a neutron and therefore they differ somewhat from the forces between a pair of identical nucleons.

One of the following sections deals with the so-called isotopic spin. The isotopic spin of a pair of identical nucleons (*pp*, *nn*) can only be equal to unity. The isotopic spin of a proton-neutron pair can take on one of two values, zero or unity. It has been established that nuclear forces operating between a proton and a neutron are precisely equal to forces between identical nucleons, provided the isotopic spin of the proton-neutron pair is unity. When an isotopic spin is equal to zero, nuclear forces between a pair of dissimilar nucleons differ from interaction forces between identical nucleons. There is the so-called isotopic invariance of nuclear forces, which will be discussed in more detail below.

The next distinguishing feature of nuclear forces is the existence of components (besides the central component) depending both on the mutual arrangement of the spins of the colliding particles and on the position of the total spin in relation to the orbital angular momentum. When the spins of two identical particles are parallel and the total spin is perpendicular to the orbital momentum there appears a component force causing mutual repulsion of nucleons. With this arrangement of the momenta and with the distance between the nucleons reduced to 1-1.5 fermis the repulsion forces may exceed those of attraction. A component of the repulsion force, which however does not exceed the attraction force, appears also when the toal spin of the two particles is antiparallel to the orbital momentum.

If we neglect cases (which are rather rare because there are many possible combinations of mutual arrangements of spins and of the orientation of the total spin in relation to the orbital momentum) when rather large forces of repulsion act over great distances and there are forces depending on the orientation

of the particles, then, to a first approximation, particularly with relatively large distances (0.7 to 1.5 fermis), the forces can be described by the exchange force theory developed by H. Yukawa.

When the distances between nucleon centres are small (0.4-0.6 fermi), the repulsion forces are very strong. The central part of a nucleon is almost incompressible. The nature of repulsion forces is not known yet.

On the whole, despite the tremendous progress in experimental investigation of nuclear forces, the physicists are still very far from the understanding of their origin. The problem of the nuclear forces, which has demanded so much energy, equipment and money, has not yet been solved completely.

Virtual Processes and Nucleon Structure

The unexpectedly high magnetic moments of the proton and neutron (2.79 nuclear magnetons instead of one for the proton, and —1.913 instead of zero for the neutron) point to a non-uniform distribution of the charge and mass in them. In the nucleon the charge is distributed more sparsely than its mass, which is concentrated in the central part. The existence of the magnetic moment in the neutron indicates that the particle is neutral only on the average and actually has a complicated charge structure. The most precise measurements of charge volume distribution in the proton and neutron have been carried out at Stanford University under the guidance of Professor R. Hoffstadter, who received the Nobel Prize in physics for these investigations in 1961.

Hoffstadter bombarded protons and neutrons (the latter in a deuton) with an electron beam of very high energy. The electron accelerator at Stanford University can accelerate electrons to energies of 2 GeV. Due to the high energy of the electron beam Hoffstadter managed to penetrate into the very heart of the nucleon.

The de Broglie wavelength corresponding to an energy of 2 GeV can be calculated by equation (3), replacing the impulse by the electron energy divided by the light velocity:

$$\lambdabar = \frac{\hbar}{p} = \frac{\hbar c}{E} = \frac{10^{-27} \times 3 \times 10^{10}}{2 \times 10^{9} \times 1.6 \times 10^{-22}} \simeq 10^{-14}\text{cm} =$$
$$= 0.1 \text{ fermi}$$

This value indicates approximately the possible accuracy in measurements in the interior of the nucleon with the aid of electrons of such energy.

According to the data obtained, the central portion of the proton carries about 10 to 12 per cent of the positive charge, and so does the central part of the neutron.

The main part of the proton charge, about 60 per cent, is concentrated in a sphere of radius about 0.8 fermi. The outermost layers of the proton carry about 28 per cent of the charge (see Fig. 20).

When speaking of exchange forces binding the nucleons in nuclei we mentioned pi-mesons, which are born at the expense of the proper energy of the nucleon and exist for a short time (about 10^{-23} sec). The nucleon can borrow some energy from itself for a short period. This process is possible due to the uncertainty principle. The greater the borrowed energy, the shorter the time for which it can be retained. If nucleons come in contact with each other (when a nucleon is within the reach of an adjacent nucleon, i.e. during

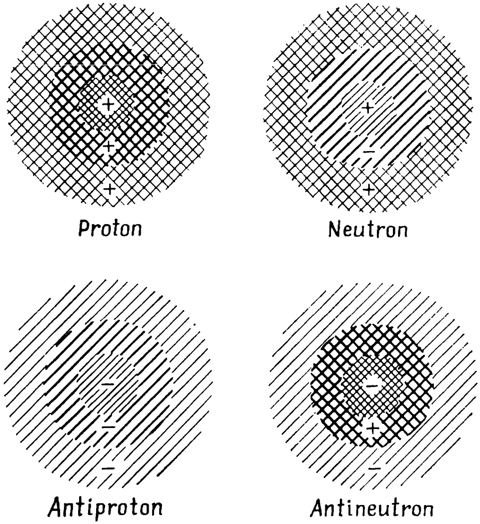

Fig. 20. The proton is charged positively on the whole: the central portion, of radius about 0.2 fermi, contains 10 per cent of the charge; the remaining charge is carried by two parts of the meson cloud; the internal part, of average radius about 0.8 fermi, has a charge approximately twice as great as the external part of radius about 1.4 fermis.

The neutron is electrically neutral on the whole, the central portion has a weak positive charge, the internal meson cloud carries a negative charge, the external part has a weak positive charge.

The antiproton is charged negatively on the whole, it is built similarly to the proton, the only difference being that both parts of the meson cloud carry negative charges.

The antineutron is negative on the whole, the charges are distributed as in the neutron, but where the neutron has a plus the antineutron has a minus, and vice versa.

the time at the disposal of a virtual pi-meson, it manages to cover the distance to the adjacent nucleon)

the virtual pi-mesons formed at the expense of their proper energy bind them together. But what if there is no adjacent nucleon? Then the appearing virtual mesons are absorbed by the nucleon which has given birth to them. This process goes on continuously: the nucleon is surrounded by a cloud of pi-mesons which are born and absorbed all the time. In the proton the pi-meson cloud is charged positively. But besides positive pi-mesons, there is presumably a cloud of neutral pi-mesons. When two protons come in contact they exchange a neutral pi-meson. The meson shell of the neutron contains both positive and negative pi-mesons. It also includes neutral pi-mesons. But this is not all. The positive and negative pi-mesons forming the meson cloud of the nucleon carry an electric charge and simultaneously provide nuclear forces; consequently, the electric and nuclear sizes of the nucleon should coincide in a "pure" pi-meson cloud. But experiments have revealed that the electric and nuclear sizes are slightly different. Theoreticians have resolved this contradiction by assuming that, in addition to the pion cloud, the shell contains two more types of unknown neutral mesons heavier than pi-mesons. As has already been noted, one of them—the omega-meson with a mass of 1530 em and a lifetime of about 5×10^{-23} sec—was discovered in 1961 after a thorough study of 30 000 bubble chamber photographs. Ninety photographs showed tracks of annihilation products of two nucleons, which can be described assuming the existence of an omega-meson disintegrating into three pi-mesons: three neutral (pi-zero) mesons or a neutral, a positive (pi-plus), and a negative (pi-minus) meson. The difficulty of detecting an omega-meson is aggravated by the fact that it is neutral, very short-lived, and leaves no track in a bubble chamber; its existence can only be judged by the tracks

of its product particles. In the second part of 1961 a similar method involving the counting of tracks of product pi-mesons led to the discovery of another meson, the rho-meson (ρ-meson) which can exist in three forms: neutral, positive, and negative. The mass of the rho-meson is about 1500 em. Its lifetime to disintegration into two pi-mesons is about ten times as short as the lifetime of the omega-zero-meson ($0.5 \times \times 10^{-23}$ sec), it is also of the order of nuclear lifetime.

We have spoken of several particles constituting the meson structure of the nucleon, neglecting their mass. If it is calculated arithmetically, it proves to be very great. But, since we are dealing with virtual processes, this should not bother us. Great masses appear for a short time, and on the average, the mass of the meson cloud is not great. In the nucleon, omega- and rho-zero-mesons also exist as virtual particles.

Is it possible to record virtual phenomena directly, for instance by photographing a virtual meson in some way or other. A virtual meson appears for a period allowed by the uncertainty relation: $\Delta E \Delta t \geqslant \hbar$. The shorter the period of time, the greater the uncertainty in energy. If we wished to photograph a virtual meson using some phantastic camera, the exposure would have to be less than the meson lifetime. In this case, however, the uncertainty in energy would increase by as many times as the exposure of the "camera" is less than the meson lifetime. Hence, the indeterminacy in the energy value obtained would be several times as great as the proper energy of the meson; we would not be able to say anything definite about it. But knowing the mass of the pi-meson, its charge and the time of its virtual life, scientists calculate its effect on the properties of the nucleon. This calculation is not easy to understand if we draw an analogy with macroscopic processes, but that's the

way things are in the microworld and it is not the only unusual phenomenon there.

In 1963 a 6-GeV electron accelerator was started at Cambridge, USA. It became possible to decrease the de Broglie wavelength of the electron by a factor of 3 and thus increase the accuracy of measurement. In December of 1963 a paper was published which investigated the nucleon structure around its centre more accurately than ever before. (In early experiments the accelerator produced electrons with an energy of 4 GeV.) Accurate measurements did not reveal, over a radius of 0.2 fermi, any special features in the nucleon structure that had been attributed to it previously. All properties of the nucleon change gradually along its radius. The nucleon has a gelly-like structure, but its charge and mass are not distributed uniformly over the volume. As we have said before, at short distances there are greater repulsion forces, whose nature is not clear yet.

Strong, Electromagnetic, and Weak Interactions

Nucleon interactions with the participation of pi-mesons are called strong interactions. They occur in the formation of pi-mesons and nucleons and also on scattering of these particles. We will see further on that strong interactions give rise to mesons heavier than pi-mesons and hyperons—particles heavier than nucleons—and lead to scattering of both on collision with each other. In order to characterize interactions between particles scientists choose an interaction constant which has the same dimensionality as the electric charge; then the interaction intensity is charac-

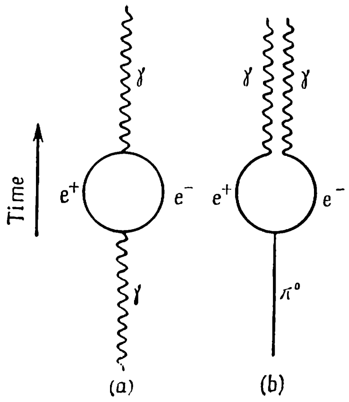

Fig. 21. Virtual birth of an electron-positron pair by a gamma-quantum *(a)*. Disintegration of a pi-zero-meson into gamma-quanta *(b)*.

terized by a dimensionless magnitude equal to the ratio of the square of this constant to the product $\hbar c$. For strong interactions this dimensionless magnitude is approximately equal to unity. Experiments on scattering of pi-mesons from nucleons have shown that the square of the constant of strong interaction is about 14. This magnitude characterizes any strong interaction assuming that all such interactions are equal in intensity.

In addition to strong interactions there are also electromagnetic and weak interactions. For electromagnetic interactions the dimensionless constant is equal to the square of the electric charge of the particle divided by $\hbar c$, i.e. it equals 1/137. When comparing the intensity of interactions this value is confronted with the square of the strong interaction constant,

which is equal to about 14. The ratio of the square of the strong interaction constant to 1/137 is about 2×10^3. The square root of the ratio of the constants is $\backsim 45$. Strong interactions are assumed to be about two orders of magnitude stronger than electromagnetic ones.

An example of electromagnetic interaction is the annihilation of an electron-positron pair. Electromagnetic interaction can involve only charged particles because uncharged particles do not interact with the electromagnetic field. But how shall we explain then the disintegration of the neutral pi-meson into gamma-quanta? It is neutral, isn't it? Virtual processes come to our aid. It is believed that a neutral pi-meson virtually emits and absorbs electron-positron pairs. It is these pairs that interact with the electromagnetic field. But one may say that this phrase, as well as the statement that an electron and a positron annihilate forming photons, is not very clear. What has this to do with electromagnetic interaction? Where does the electromagnetic field come from? Nothing has been said about it, only an electron-positron pair being mentioned. The thing is that each ordinary electron, like an ordinary positron, emits and absorbs virtual particles, in this case photons. And photons are electromagnetic field quanta.

When an electron encounters a positron the entire proper energy of the pair converts into the energy of two photons. Why two, and not one then? Because the emission of two photons is in line not only with the law of conservation of energy, but also with the law of conservation of impulse. If an electron and a positron approach each other with equal velocity, the total impulse of the pair will be zero relative to their meeting point. Upon annihilation the impulse will not be zero if only one photon is born. Two pho-

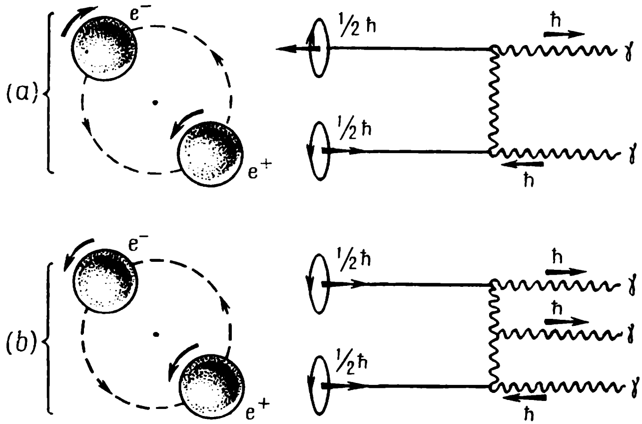

Fig. 22. Electron-positron annihilation into two and three gamma-quanta. Prior to annihilation the electron and positron form a positronium for a short time; it is a sort of an atom in which an electron and a positron rotate about their common centre of gravity: (a)—the electron and positron spins in the positronium are antiparallel, annihilation results in two gamma-quanta with antiparallel spins; (b)—the spins of the initial particles are parallel, three gamma-quanta are born, their total spin is unity as with the initial particles.

tons flying apart with equal velocity away from the point where annihilation occurred will yield a zero total impulse.

But sometimes an electron-positron pair annihilates into three photons. This happens because in an annihilation reaction, as in any physical event, the law of conservation of angular momentum must be observed as well as the laws of conservation of energy and of momentum. An electron-positron pair rotates about their common centre of gravity for some time before they annihilate. This complex is called

a positronium because a pair in this state resembles an atom.

Assume that the orbital momentum of a positronium is zero, the positronium is in the *s*-state. This happens whenever the initial relative velocities of the particles are rather low. Then, with the electron and positron spins antiparallel (such a positronium is called a parapositronium), the initial angular momentum is zero. Upon annihilation two photons having a unit spin each and arranged antiparallel also yield a zero angular momentum. The law of conservation is observed. Now assume that the electron and positron spins are parallel (orthopositronium). In this case the total angular momentum of the positronium will be equal to unity.

If two photons appear upon annihilation, the law of conservation of angular momentum cannot hold good. The spins of the two photons may total up to zero if they are antiparallel, or to two if they are parallel. For the law of conservation of angular momentum to be valid, three photons are necessary. Two of them, the antiparallel ones, will yield a zero spin, and the third, a unity, as required by the law of conservation of angular momentum, with parallel electron and positron spins in a positronium. With three photons available it is possible to satisfy (at least as readily as with two) the requirements of the laws of conservation of energy and of momentum as well. When we have an orbital angular momentum the picture is more complicated. But it is sufficient to consider the *s*-state to understand the cause for annihilation into two or three photons.

The lifetime of an orthopositronium (spins parallel) to annihilation is equal to 1.4×10^{-7} sec, that of a parapositronium (spins antiparallel), to about 10^{-10} sec. This difference in lifetime is due to the fact that

three-quantum annihilation of an orthopositronium is about 1000 times less probable than two-quantum annihilation of a parapositronium.

We have wandered away from the subject, i.e. the role of virtual processes in electromagnetic interactions. Note that interaction of a single electron with an electromagnetic field can also be explained by interaction of the field with the virtual photons of the electron. There is a proof of virtual emission and absorption of gamma-quanta by an electron. Quantum electrodynamics enables one to calculate the effect of virtual events on the magnetic moment of an electron. Neglecting the virtual events, the spin magnetic moment of an electron is equal to one Bohr magneton. If we take these events into account, the magnetic moment will be 1.0011614 Bohr magnetons. Experiment confirms the latter figure, thereby proving the validity of the assumption of virtual emission and absorption of gamma-quanta by an electron.

If the square of the dimensionless constant which determines the interaction intensity is equal to about 14 for strong interactions and 1/137 for electromagnetic ones, it is only about 10^{-13} for weak interactions.

Strictly speaking, the constant of weak interaction, which is responsible for the slow disintegration of particles, is not a dimensionless magnitude. For beta-disintegration this constant is equal to 1.4×10^{-49} erg.cm^3. All other slow disintegrations are assigned the same constant assuming a universal character of weak interaction. To obtain a dimensionless value which can be compared with dimensionless constants characterizing strong and electromagnetic interactions, the dimensional constant is divided by a value of the same dimensionality consisting of the universal constants $\hbar$ and c and also of the Compton wavelength of the pi-meson. As a result we obtain 2.4×10^{-7}. The

square of this value, which can be compared with the above squares of constants of interaction of other types, is equal to about 6×10^{-14} or, rounding off, 10^{-13}.

An example of weak interaction is disintegration of a neutron into a proton, an electron, and an antineutrino. This disintegration takes a very long time compared with nuclear times. Indeed, a nucleon flying past another nucleon is within the range of nuclear forces for a time of the order of the range of these forces divided by the velocity of the nucleon, which is approximately equal to the light velocity. Dividing 1.4×10^{-13} by 3×10^{10}, we obtain about 5×10^{-24} sec, or, rounding off, 10^{-23} sec. This is the time characteristic of strong interaction, it is smaller by many orders of magnitude than the lifetime of a neutron. Accordingly, the forces causing the disintegration are also smaller. To estimate these forces it is useful to consider other cases of weak interaction. Weak interactions include disintegration of other elementary particles. Charged pi-mesons live 2.55×10^{-8} sec. Later on we will deal with particles disintegrating within about 10^{-10} sec. The shortest lifetime of particles disintegrating as a result of weak interactions (10^{-10} sec) is about 10^{13} times as great as the time of strong interactions (10^{-23} sec). Hence the interaction constant is estimated at about 10^{-13}. For comparison sake we will note that the lifetime of the omega-zero-particle, which is equal to about 10^{-23} sec, and that of the rho-zero-meson (10^{-22} sec) points to their disintegration into pi-mesons as a result of strong interactions. Particles disintegrating as a result of electromagnetic interactions, such as the neutral pi-meson, also live considerably less than 10^{-10} sec.

Assuming the existence of a strong-interaction carrier (a pi-meson, and also omega- and rho-meson) implies a non-local nature of this interaction, i.e. its

spread in space and time. True, until a complete strong-interaction theory is developed, one cannot establish the local or non-local nature of these interactions with a sufficient degree of confidence. At this juncture we cannot even say whether there is one universal type of strong interactions or there are several types.

The weak-interaction theory has advanced slightly further than the strong-interaction theory. One of its great achievements is the understanding of the fact that all weak disintegrations whose lifetimes lie within the range from 10^{-10} sec to thousands of millions of years (they vary by 26 orders of magnitude) are due to one and the same process—universal weak interaction. As regards the local or non-local nature of weak interaction, this problem is not yet clear. If it is local, then the relevant distance may be of the order of 10^{-17} cm (or slightly greater). A local nature implies that for a particle to disintegrate, certain fields responsible for it must interact at a spot having a diameter of about 10^{-17} cm. If the local nature of weak interaction is confirmed, the smallest of all known characteristic sizes of microparticles will be established. It will be smaller than the gravitation radius of an elementary particle.

If weak interaction is non-local, the cause is the exchange of a heavy intermediate particle, an intermediate meson. Its spin is equal to unity (this is a boson), it has a unit electric charge. At present, an intensive search is going on for the intermediate boson responsible for weak interaction, and it can only be said that its mass (if it is discovered) will be at least 1,3 GeV, otherwise it would have been recorded by now.

Parity, Its Conservation and Non-Conservation

In quantum mechanics the state of a particle or of a system of particles is characterized by a certain function of the coordinates and time—a wave function determined by solving the Schrödinger equation. For instance, the probability of detecting a particle at a definite site is equal to the square of the wave function (more precisely, the square of the modulus of the wave function).

The parity of a state, or the parity of a wave function relative to spatial inversion, is positive (+1) if the sign of the wave function does not change on changing the positive coordinates to negative ones (x to $-x$, y to $-y$, and z to $-z$). If on this change the sign changes too, the parity is negative (—1). The parity of a function has been familiar to mathematicians for a long time. For instance, the functions $y=\cos\alpha$ and $y=x^2$ are even. The replacement of α by $-\alpha$ and of x by $-x$ will not change the sign of the function. On the other hand, the functions $y=\sin\alpha$ and $y=x^5$ are odd: the replacement of α by $-\alpha$ and of x by $-x$ changes y to $-y$. From the Schrödinger equation it follows that for all cases where the energy of a system or particle is conserved, the parity is conserved as well. Therefore, until 1957 the law of conservation of parity was considered as unshakable as the law of conservation of energy. The schemes of all processes in which parity is not conserved were rejected just as any scheme of perpetual motion has been rejected for a long time without even investigating it.

So far we have not cleared up the physical meaning of parity conservation. Formal statements and definitions will hardly elucidate the matter. The law of

conservation of parity implies that nature makes no distinction between right-handed and left-handed reference systems. Indeed, replacement of all positive coordinates by negative ones is tantamount to conversion from a right-handed reference system to a left-handed one. But the choice of a reference system is a matter of personal taste. We usually use a right-handed system only because we are accustomed to it. For instance, if we change a right-handed system to a left-handed one the electron spin will switch over to the opposite direction. A system is chosen arbitrarily, but natural processes cannot depend on our arbitrary choice, they proceed in the same way, no matter what reference system we use to describe them. A function describing the state of a system up to a certain transformation, with the parity preserved, reacts to a change of the reference system in the same manner as a function describing the state of the system after transformation. This means that the system is indifferent to the choice of a reference system. But imagine that parity changes in some process or other. This would mean that a particle or a group of particles have "found out" about the change of the reference system and reacted to it accordingly; the function describing the state would then behave differently. For instance, formerly it did not change sign on change of the reference system, its parity was positive, and now, "having found out" about the change, it would react by changing sign, and its parity would become negative.

Let us consider a more specific example. Suppose we have a spherically symmetric nucleus possessing a certain spin; even not one nucleus, but a set of absolutely identical nuclei which are all ready to emit absolutely identical gamma-quanta after some time. Since the nucleus possesses a spin, something must be

rotating in it, there are some circular currents of matter. Therefore, neglecting the equatorial regions of the nucleus (just in case) we will consider only its two poles and see from which pole gamma-quanta will be emitted more readily. It could be argued that spins have their direction. Maybe photons will like to fly along the direction of the spin? Then most of the nuclei within our field of vision will emit photons along the direction of the spin. But we have determined this direction arbitrarily. Let us change the reference system and determine the spin not in the right-handed, but in the left-handed system. Then it will be oriented in the opposite direction. Since the nucleus remains "ignorant" of the change, it does not know the direction of the spin, which depends on our choice, and emits gamma-particles through both poles with equal probability. Indeed, when emitting gamma-particles the nucleus "does not know" the right from the left. This law used to be considered unshakable for all types of interaction—strong, electromagnetic, and weak.

The Chinese scientists T.D. Lee and C.N. Yang when thinking over certain queer phenomena which occur in disintegration of strange mesons (K-mesons) questioned the validity of the law of conservation of parity in weak interactions and proposed several experiments for its practical verification.

In order to check whether the same number of electrons is emitted from each pole in beta-disintegration —a typical process for weak interactions—they lined up the spins of cobalt-60 nuclei in one direction (polarized them) and measured the number of beta-particles flying along the direction of the spin and opposite to it. The experiments revealed that in the right-handed system electrons flew mostly in the direction opposite to that of the spin.

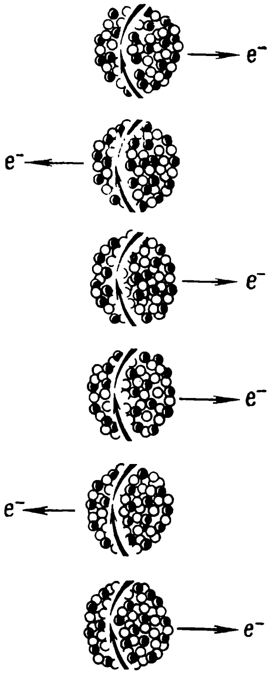

Fig. 23. Distortion of spatial symmetry in beta-disintegration of cobalt-60. The nuclei of cobalt-60, if one considers only those emitting an electron along the axis relative to which the spin is oriented, give off beta-particles predominantly in the backward direction (in the right-handed reference system).

In weak interactions nature knows the right from the left very well. This discovery, which is not fully understood even now, produced a tremendous impression on the scientific world. Non-conservation of parity was discovered not only in beta-disintegration,

but in all weak interactions in general; it is observed, for instance, in disintegration of charged pi-mesons and strange particles.

At present it is believed that non-conservation of parity may sometimes be observed also in strong interactions, for instance in fission of atomic nuclei under certain conditions.

Non-symmetry occurring in nature, at any rate in weak interactions, placed the physicists in a very difficult position. Academician L. Landau, the eminent Soviet physicist and Nobel Prize winner for 1962, came to the rescue. He suggested that nature is not so primitive as was usually thought. Soon after the conclusions of Lee and Yang were published and the first experiments were staged in 1957, Landau advanced the hypothesis that the apparent asymmetry was due solely to the fact that matter was considered separately from antimatter. If they were considered jointly, symmetry would be retained. This concept received the name of combined inversion. If we line up the nuclei of antimatter exactly in the same way as the nuclei of matter, beta-particles in antimatter (now they are positrons in place of the electrons in matter) will be emitted largely in the direction opposite to the emission of beta-particles in matter. Thus, if we observe the same number of oriented nuclei of matter and antimatter and neglect the charge sign of the emitted beta-particles, spatial symmetry will not be distorted. Landau's conclusion found indirect experimental confirmation. Direct experiments with antimatter are not feasible as yet.

The idea of combined inversion is extremely attractive and convincing. Indeed, considering matter alone separately from antimatter we flagrantly violate the symmetry of the world. This is tantamount to observing one of its halves and ignoring the other, equiva-

lent one. It seems quite logical that nature voices its objection to this discrimination towards its legitimate half. But these considerations are prompted solely by intuition. The real cause for the distortion of spatial symmetry is not clear at this stage. In August 1964, at the International Conference on High Energy Physics in Dubna (USSR) proofs of non-conservation of parity and of combined parity were given. When, after combined inversion, i.e. replacement of particles by antiparticles and spatial inversion of coordinates, the wave function of a particle (or a system of particles) changes sign it is said that its combined parity (which is denoted as *PC*, or *PC*-parity) is negative, it is equal to —1.

If the sign does not change, the *PC*-parity is positive, it is equal to +1. The conservation of combined parity means that if, prior to the reaction of transformation of one type of particle into the other, the combined parity was negative (—1), it must remain negative for the transformation product as well. A positive combined parity of the initial products is associated with a positive combined parity of the end products of the reaction.

The combined parity of the K_2^0-meson, which the reader will encounter in one of the following sections, is negative (—1). This particle disintegrates into pi-mesons (there are also disintegrations into lighter particles, but they are of no consequence here). A combined parity of two pi-mesons (π^+ and π^-) is positive, while in a system of three pi-mesons it is negative. The law of conservations of combined parity allows disintegration of a K_2^0-meson into three pi-mesons and forbids disintegration into two mesons.

Quite a stir was caused at the Dubna Conference by a report of observed disintegration of a K_2^0-meson into

two pi-mesons. This disintegration is evidence of non-conservation of combined parity. If these experiments do not find some simple explanation, the physicists will face a very difficult problem, may be even a more formidable one than the problem of non-conservation of spatial parity which they were up against in 1956-1957.

Now it is impossible to effect combined inversion "secretly". It appears that nature knows all about this extremely complex operation and signals us about it, just as it does when a right-handed system of reference is replaced by a left-handed one.

It is significant that the two important discoveries of general laws of nature, which are so uniquely manifested in weak interactions, have been made in connection with investigation of *K*-mesons. These particles proved to be the core around which the most characteristic and subtle properties of the microworld and its most conspicuous quantum-mechanical manifestations are centred.

The physicists are already deriving practical advantages from the discovery of non-conservation of parity in weak interactions. In order to determine the magnetic moment of the mu-meson a beam of these particles is passed between the poles of a powerful magnet. To calculate the number of revolutions of a muon in the magnetic field one has to learn the direction of the spin after the muon has left the magnetic field and slowed down in the target. This direction is determined from the distribution of the electrons emitted by muons on disintegration. Most electrons are emitted in the direction opposite to the spin due to non-conservation of parity. The original position of the spin of the muon before it finds itself in the magnetic field is known well enough: it is oriented predominantly along the direction of the muon flight.

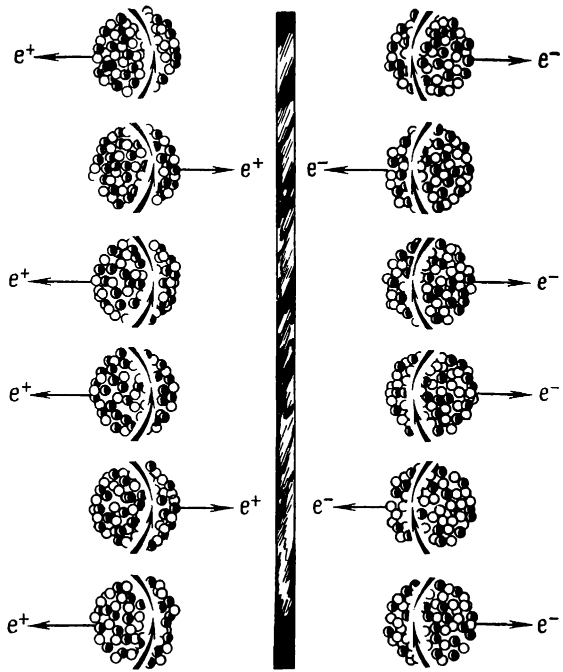

Fig. 24. Combined inversion in weak interactions. In beta-disintegration of antiparticles positrons fly back in the left-handed reference system. In beta-disintegration of particles electrons fly predominantly back in the right-handed reference system. Observing disintegrations of an equal number of particles and antiparticles identically oriented in one and the same reference system, you will see, on the average, the same number of beta-particles flying right and left, provided their charge sign is neglected.

Knowing the initial and final direction of the spin, its angle of rotation in the magnetic field is determined. This value is needed for accurate determination of the magnetic moment of the mu-meson. Non-conservation of parity in weak interactions is also utilized in other experiments with microparticles, where one has to know the orientation of the particle spin.

We will now wind up the discussion of non-conservation of parity, a phenomenon which nature has used to challenge all physicists engaged in investigation of the microworld. Due to this phenomenon weak interactions have attracted the attention of researchers.

Polarization of Vacuum

Now that we have discussed the structure of the hydrogen atom and the composition of heavy nuclei, the following picture of the structure of matter can be visualized. Atomic nuclei consist of nucleons—protons and neutrons. The nucleons are bound together by charged and neutral pi-mesons, which are virtually born and absorbed inside the nucleons all the time. Nuclei are surrounded by rotating electrons and when these shift from upper energy levels to lower ones, photons are emitted. The photons, getting into other atoms, may excite high energy states in electrons and cause them to move to outermost orbits.

Antimatter has a similar structure. Its nuclei consist of negatively charged particles—antiprotons and neutral antineutrons. Antinucleons are bound in the antimatter nuclei by the same charged and neutral pi-mesons which bind the nuclei of matter. Positive electrons (positrons) rotate about the nuclei of antimatter. When positrons in an antiatom shift from upper excited levels to lower ones, a photon is emitted,

the same photon as is radiated by an excited atom of matter.

When an electron and a positron collide they annihilate forming two or three gamma-quanta (photons). An antinucleus encountering a nucleus annihilates in several stages. At first pi-mesons are formed, and sometimes also neutral omega- and rho-particles, which very rapidly (within 10^{-23} sec) disintegrate into pi-mesons, both charged and neutral. The pi-mesons disintegrate into mu-mesons, neutrinos, and antineutrinos. The mu-mesons, having existed for 2.2×10^{-6} sec, disintegrate into electrons or positrons, depending on their charge. The emission of an electron, as well as a positron, is accompanied by the emission of two particles—a neutrino and an antineutrino.

Particles, including photons, are rather sparsely distributed in space. The medium in between is called a vacuum.

Two concepts of a vacuum should be distinguished —physico-technical and purely physical. In physical engineering and in technology the term vacuum implies a rarefied gas whose pressure is such that the range of the particles exceeds the size of the vessel. In the instrument-making industry, more precisely in vacuum technology, rarefactions (pressures) of a gas ranging between 10^{-6} and 10^{-7} mm Hg are usually achieved. At such pressures there are, respectively, about 3×10^{10} and 3×10^{9} atoms or molecules of gas per cu. cm.

Thermonuclear investigations require the deepest possible vacuum. At present, rarefactions of the order of 10^{-10} mm Hg have been achieved in large volumes. In this case there are about 10^{6} particles per cu. cm. The highest vacuum exists in interstellar space, where each cubic centimetre contains only about one particle. Interstellar vacuum is one million times better

than the most perfect man-made vacuum. Incidentally, when launching space ships one does not have to pump out and seal off electronic equipment designed for operation exclusively in space and requiring a high vacuum. It is sufficient to connect this equipment with the atmosphere and, whence in space, the gas will escape from the instrument, thus providing a degree of vacuum unobtainable on earth at present.

Rarefied gases possess a number of very interesting properties which are widely used in vacuum technology and instrument making. We, however, are interested in other properties of vacuum at the moment. One must understand, at least approximately, the meaning of the term "vacuum", a space not occupied by atoms, electrons, photons, or by any particles in general.

If we approach the problem from the philosophical standpoint, then a vacuum is a special type of matter. It exists objectively, independent of our mind, and can affect us or, more precisely, our instruments. But in order to reveal the effect of a vacuum one must possess refined equipment and an extensive knowledge. But the same can be said about the other varieties of matter. Nobody would have been able to detect elementary particles, even the proton and neutron (not to mention less accessible particles like mesons or neutrinos) if science had not reached a comparatively high level of development.

We presume the energy of the electron to be positive. Let us imagine some space completely filled with positrons. Each of the positrons is at a negative energy level. If an electron gets into this space, it lands on one of the negative energy levels just as it shifts from an upper orbit to a lower one in the atom. When an electron settles on a negative level (this is actually electron-positron annihilation) an energy is released which is equal to the energy of the electron transfer,

at first from its original level to zero, and then from zero to the negative positron level. In all, the energy released is equal to the doubled proper energy of the electron. If all the negative levels are occupied by electrons (i.e. all the positrons have annihilated with the electrons), no new electrons can be "landed" on any of them, since this is forbidden by the Pauli principle: only one electron can be on each of the levels in each of the states; since it is a fermion, its spin is equal to 1/2.

The state of matter in which all negative levels are occupied by electrons is called an electron-positron vacuum, this being an unexcited state of matter. The electrons which we encounter in practice have been raised from negative levels and are flying in space; they fail to find a negative level on which they could "land." Negative levels (positrons) exist elsewhere.

In a similar way one can determine a nucleon vacuum, for instance antiprotons—negative levels from which protons have been raised. A proton is also a fermion, it cannot "land" on a level occupied by another proton, and therefore is forced to "wander" as a proton in an excited state.

In the foregoing discussion the particle energy was assumed to be positive and that of antiparticles, negative for the sake of simplification and illustrativeness.

Some people argue that since the energy of an antiparticle is negative, so must be its mass. This allegedly negative value of the mass of antiparticles enables some scientists to assume the existence of gravitational forces of repulsion between matter and antimatter. A gravitational force acting between two bodies is proportional to the product of their masses. Since two positive masses are attracted to each other by the gravitational force, it might seem that the

positive and negative masses should repulse each other. There are, however, experimental data proving the contrary: no gravitational forces of repulsion exist between matter and antimatter; there is just the ordinary force of gravitational attraction.

In actuality there is no negative energy or negative mass. The existence of negative energy (and mass) would be in contradiction with the law of conservation of energy. Indeed, if we add the energy of a positron, assuming it to be negative, to the equal but positive energy of an electron, we obtain zero. Positron-electron annihilation yields two (or three) gamma-quanta with a positive energy instead of zero.

Besides a particle vacuum there is an electromagnetic-wave vacuum, the lowest energy state of an electromagnetic field relative to which a photon is an excited state.

At first glance a vacuum does not and cannot manifest itself in any way. But this is only the first impression. To understand how a vacuum can manifest itself one should use the concept of a virtual process. In order to raise an electron from a negative level to a positive one, i.e. for an electron-positron pair to appear, an energy slightly exceeding 1 MeV is required. A photon of this energy gives birth to a real electron-positron pair. True, the expression "a real pair" is not very suitable, it implies that the other pairs, which will be discussed below, are unreal. But since this expression is used we will also use it with a reservation. So, when the photon energy is below the birth threshold of an electron-positron pair, these particles are born virtually only for a short time to preclude the violation of the laws of conservation of energy and impulse. But what is the virtual birth of an electron-positron pair? This is merely raising of an electron for a short time from negative energy level to

a positive one. This phenomenon is termed vacuum polarization. In a vacuum, particles and antiparticles appear for a short time, as well as a positive and a negative charge. Like any virtual process, vacuum polarization cannot be observed directly because of the uncertainty relation. But this by no means implies that polarization is an unreal phenomenon. Polarization leads to effects which can be accurately measured and calculated theoretically.

In an electromagnetic vacuum virtual processes can also be observed; one of them is the appearance of virtual photons, or electromagnetic field fluctuation. This fluctuation occurs particularly readily under the effect of an electron.

As we have already said, the spin magnetic moment of the electron is slightly higher than we expected when we neglected virtual photons. If we take them into consideration, the magnetic moment proves to be 0.001145 Bohr magneton higher, and this agrees with experiment. It is the first confirmation of the vacuum effect.

Another experiment confirming the existence of the vacuum effect is the shift of the energy levels which is referred to as the Lamb shift. With the principal quantum number equal to two an electron in a hydrogen or a deuterium atom can be in either one of two states: $2s$ and $2p$. In the first state the orbital momentum is equal to zero, in the second to unity. In the absence of an external magnetic field these levels correspond to one and the same energy, or to the same frequency. W. Lamb measured both levels very precisely in 1947 and found that the $2s$-level is shifted 1058 MHz, or 0.033 1/cm upwards from the $2p$-level. It should be recalled here that we are speaking about the $2^2p_{1/2}$-state, where the electron spin on the $2p$-level is antiparallel to the orbital momentum. The

$2p$-state proper splits up into two states: one with a spin antiparallel to the orbital momentum, and the other with a spin parallel to it: $2^2p_{1/2}$ and $2^2p_{3/2}$ respectively. We will recall the meaning of the symbols using the $2^2p_{1/2}$-state. Here the first figure 2 means the principal quantum number: the electron is in the second shell; the second figure 2 at the upper left of the letter p indicates that the state is one of a doublet; the letter p means that the orbital momentum of the electron is unity. The fraction 1/2 at the lower right of the p indicates the magnitude of the total angular momentum of the electron. In this case the electron spin is antiparallel to the orbital momentum, and the total momentum is equal to 1/2. The second compound of the doublet ($2^2p_{3/2}$) has a total angular momentum of 3/2; here the spin is parallel to the orbital momentum. The Lamb shift is observed in the $2^2s_{1/2}$-level relative to $2^2p_{1/2}$. This shift cannot be explained without taking into account virtual vacuum phenomena. But it can be fully explained if one takes into consideration the interaction of the electron with the electromagnetic fluctuations of the vacuum (the greater portion of the effect) and with electron-positron virtual pairs (the smaller portion).

We have thus taken a peep at a very complicated field, that of quantum electrodynamics, a science which has probably reached the greatest degree of perfection as compared with the other branches of quantum physics which deals with elementary particles and their interactions. Here we will wind up our brief and superficial survey of this science.

List of Elementary Particles Playing a Definite Role in the Structure of Matter

In the preceding sections we encountered a rather great number of elementary particles. All of them are in some way or other involved in the structure of matter (and antimatter) or determine the forces operating between other particles. Only one pair of particles, mu-mesons, carries a rather light load, it serves exclusively as an intermediate stage in disintegration of pi-mesons into electrons and neutrinos. It is now time for us to put all this information in order. In the future we will come across a great number of other, so-called strange particles, and it will be difficult to find our way in such a jungle. We will do our best to reduce this difficulty to a minimum.

Table 2 includes all known elementary *non-strange* particles, except short-lived ones (resonances)—mesons (ω, ρ, and others) and baryons disintegrating as a result of strong interactions.

We have told you quite a lot about nucleons and pi-mesons, and did not do justice to the other particles. Now we will make amends by briefly outlining certain properties of the photons and leptons.

PHOTON

The photon is a very pictorial example of the dual wave-corpuscular nature of matter. The wave properties of light are most convincingly confirmed by the phenomena of interference and diffraction of light.

As far back as the beginning of the last century interference was explained by the wave properties of

TABLE 2
NON-STRANGE ELEMENTARY PARTICLES

Class and name	Particle symbol	Antiparticle symbol	Spin	Mass		Mean lifetime, sec
				MeV	em	
Photon	γ	γ	1	0	0	Stable
Leptons:						
electron neutrino	ν_e	$\tilde{\nu}_e$	1/2	0	0	ditto
muon neutrino	ν_μ	$\tilde{\nu}_\mu$	1/2	0	0	ditto
electron	e^-	e^+	1/2	0.511	1	ditto
muons	μ^-	μ^+	1/2	105.7	206.8	2.2×10^{-6}
Mesons:						
pions	π^0	π^0	0	135.0	264.2	1.9×10^{-16}
	π^+	π^-	0	139.6	273.2	2.5×10^{-3}
Nucleons:						
proton	p	$\tilde{p}$	1/2	938.2	1,836.1	Stable
neutron	n	$\tilde{n}$	1/2	939.5	1,838.6	1.01×10^{3}

light. If two light waves hit the same spot, but so that the oscillations in one of them are directed opposite to those in the other (they are in antiphase), the light becomes weaker; when the oscillations coincide in direction, they become stronger. Two beams which have issued from the same source but traversed different paths before they meet gain in strength if their propagation difference is equal to the wavelength of light or to an integral number of wavelengths, and weaken if the propagation difference is equal to a half-wavelength or to an integral number of half wavelengths. Therefore, for instance, a thin film of oil or kerosene on the surface of water has a slight colouring. A beam reflected from the surface of the oil traverses

a shorter path than one reflected from the water. The smaller the angle at which we look at a water surface covered with an oil film, the greater the propagation difference of the beams, therefore the colour of the film changes when we look at different angles.

Diffraction is the circumvention of an obstacle by light beams, their "bending around the corner". Diffraction and interference can be explained exclusively by the wave properties of light.

The corpuscular properties of light are most prominently manifested in a phenomenon discovered in 1923 by A. Compton, who later became one of the makers of the atom bomb in the USA. Compton observed scattering of X-rays from electrons of graphite and paraffin. If the energy of X-rays is high, one can assume with sufficient degree of assurance that their quanta scatter from free electrons. Compton noted that the frequency of scattered rays is lower than that of incident ones, and the magnitude by which the frequency decreases depends on the angle at which the scattered rays are measured. The Compton effect can be calculated very accurately if we assume that X-rays consist of particles—photons—possessing not only an energy but also an angular momentum equal to $\hbar\nu/c$, i.e. the photon energy divided by the light velocity. In the Compton effect, the photon and electron behave as two particles and when they collide the laws of conservation of energy and momentum are obeyed. The photon loses as much as the electron gains. The Compton effect is a conclusive proof of the corpuscular properties of light.

For the first time the corpuscular nature of the photon was clearly defined by A. Einstein in 1905. Since the photon has an energy and a momentum, it also possesses a mass, which is equal to its energy divided

by the square of the light velocity. But it has no rest mass. One cannot imagine a photon at rest. It is always flying with the velocity of light. The spin of the photon, its proper angular momentum, is equal to unity. Therefore the photon, in contrast to fermions (particles with a spin of 1/2) does not obey the Pauli principle. In any state, for instance in a given space, there may be an arbitrary number of absolutely identical photons.

The fact that the photon has a unit spin affects the light spectra emitted by atoms. Light is emitted on transfer of an electron from an upper level to one of the lower levels. When a photon is emitted the laws of conservation of energy and momentum operate without a hitch. But in mechanics, in the field of central forces (the electrons in the atom are precisely in such a field) the law of conservation of angular momentum should also hold good. A photon carrying away an angular momentum equal to its spin will change the angular momentum in the atom. One of the ways to effect this change could be a reduction by unity in the orbital angular momentum of an electron in the shell. Therefore in complex atoms light emission and electron transfers in general require an additional condition: upon emission of a photon the orbital angular momentum should change by unity. Therefore, for instance, transitions from upper P-levels to lower S-levels or from D- to P-levels are possible, but transitions $S \rightarrow S$ or $P \rightarrow P$ are forbidden. In the latter case there is no source for an angular momentum needed to form a photon spin. But there may be exceptions. For instance, in the hydrogen atom, when the electron and the proton have a spin of 1/2, an angular momentum necessary for the formation of a photon spin may appear if the electron and proton spins were antiparallel prior to photon emission and parallel after

emission. The spin of the system changes by unity. A photon can be born also upon an $S \rightarrow S$ transition. But this is a very rare event, its probability is low, since transitions without a change in orbital momentum are forbidden. However, this prohibition is not absolute.

LEPTONS

Both types of neutrino, the electron and the negative mu-meson, together with their antiparticles (the two antineutrinos, the positron, and the positive mu-meson) are called leptons, i.e. light particles, although the muon is actually not so light. All leptons are fermions with a spin of 1/2. The leptons have a distinguishing feature, they do not take part in strong interactions either among themselves or with other particles. Charged leptons enter into electromagnetic interactions and all of them take part in weak interactions. It was previously thought that weak interactions are the monopoly of leptons. But later it transpired that weak interactions can take place without the participation of leptons. Examples are disintegration of particles into pi-mesons alone or into pi-mesons and heavier particles.

The leptons obey the law of conservation of leptons; to be more precise, this law governs all reactions in which leptons appear or disappear. According to this law, if a nuclear reaction results in a certain number of leptons, the same number of antileptons should be born. They disappear also together and in equal numbers. For instance, on disintegration of a neutron one lepton (an electron) is born. This is accompanied by the appearance of an antilepton (an antineutrino). On disintegration of a negative mu-meson one lepton (a mu-meson) disappears, and another lepton (an electron) appears. A neutrino is born in this reaction,

however, so that the law of conservation of energy and momentum can be fulfilled. According to the law of conservation of leptons, a neutrino cannot be born in this reaction without the appearance of the corresponding antineutrino. The mu-meson thus disintegrates into an electron, a neutrino, and an antineutrino.

NEUTRINO

The neutrino is the lightest of the leptons; it is a very interesting particle which is the symbol of the great potentialities of theoretical physics. As you probably know, radioactivity was discovered in 1896 by Antoine Henri Becquerel, French Academician, representative of the third generation of the Becquerel dynasty of physicists. His grandfather, father, and also his son, Jean Becquerel, were prominent French scientists.

After Becquerel had discovered the radioactivity of uranium numerous investigations revealed the existence of three types of radioactivity: alpha-, beta-, and gamma-activity. Upon alpha-disintegration the nucleus emits an alpha-particle (a helium nucleus). The disintegration is not accompanied by the birth of a new particle: the two protons and the two neutrons comprizing the alpha-particle emitted by the nucleus already existed there before. The process proved to be relatively simple and did not cause any special excitement. In gamma-radioactivity, the nucleus emits a gamma-quantum, or a photon. The photon is born in the nucleus; in principle this event has been familiar to scientists for some time: a photon was also born in an atom on transfer of an electron from an upper to a lower orbit. The investigators quickly understood that in gamma-radioactivity the nucleus rids itself of excess energy by emitting it as a gamma-

quantum. When considering alpha- and gamma-disintegrations there were no contradictions with the laws of conservation of energy, momentum, and angular momentum. These fundamental laws remained unshakable.

Radioactive beta-disintegration proved to be a much more complex phenomenon, where the nucleus not only emits a particle which was there before as in alpha-disintegration. In beta-disintegration a new particle—an electron—is born. Moreover, calculations of energy, momentum, and angular momentum of the initial nucleus and of the disintegration products—the final nucleus and electron—showed that a balance is never maintained and it diverges by a different value each time. The nucleus of one and the same radioactive isotope emits beta-particles (electrons) of different energy, from a certain maximum to zero energy. At the same time the final nucleus is always the same, with the same energy in all cases. The original nucleus, in converting into the final one, always loses the same energy, which is precisely equal to the maximum possible energy of the emitted electron, while the energy of the latter is different in different cases. Where then does the energy go when the electron energy is below the maximum? Many scientists used to think that the law of conservation of energy could not be applied to beta-disintegrations. Moreover, if we calculate the impulse of the original nucleus and the total impulse of the final nucleus and electron emitted, the balance diverges here too, the impulses are always different in practice. The impression was that the law of conservation of momentum was also violated. The angular momentum was not conserved either. For instance, the artificial radioactive element carbon-14, whose spin is equal to zero, disintegrates into an atom of nitrogen-14 with a unit spin and an

electron with a spin of 1/2. No matter how you orient the spins of the nitrogen atom and an electron relative to each other you will never obtain zero. With a parallel orientation of spins, the total spin is equal to 3/2, with an antiparallel orientation, 1/2. Neither the first, nor the second value is equal to the spin of the initial particle (zero).

The physicists were striken with panic. This may be an overstatement, but they were really at a loss and far from unanimous in their opinions. The Swiss physicist Wolfgang Pauli (who had formulated his principle in 1925 when he was only 25 years old), being firmly convinced of the universality of the laws of conservation of energy, momentum, and angular momentum, straightened out the situation again. In 1933 he postulated the existence of a then unknown neutral particle with a near-zero rest mass. It was found later that its mass was equal to zero, as well as the mass of the photon. This particle has a spin of 1/2 and carries away the very energy which seemed to disappear, thereby restoring the balance of the impulse and angular momentum. In the example on disintegration of carbon-14 the appearance of a neutrino (in this case antineutrino) with a spin of 1/2 fitted the reaction into the law of conservation of angular momentum and the other laws of conservation. The spins of an electron and an antineutrino are oriented identically and total up to unity. The total spin, taking an antiparallel position relative to the spin of nitrogen, yields the total spin of disintegration products, equal to zero, as in the original nucleus of carbon-14. The Pauli hypothesis was brilliantly confirmed: the assumption of the existence of a neutral particle fully explained all experimental facts, and the laws of conservation proved unshakable; the physicists had a load off their shoulders. In the same year of 1933,

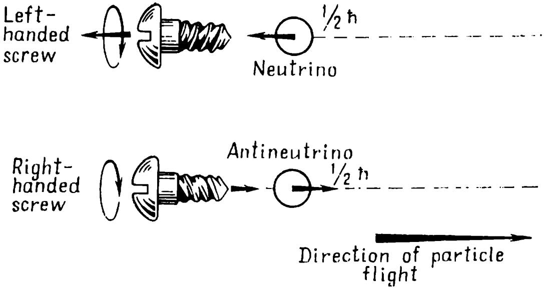

Fig. 25. The neutrino is a left-handed particle, the antineutrino being right-handed.

after the neutron was discovered, Enrico Fermi, who was developing the theory of beta-disintegration with the participation of a light neutral particle, named it the neutrino, which means a small neutron in Italian.

Later on, a need for the antineutrino arose. According to Dirac, who had found the necessary experimental confirmation, the spin of the neutrino is directed opposite to the flight of this particle, and its direction is thus opposite to that of the particle impulse (the impulse is directed along the velocity of the particle). If the direction of movement of the impulse is used as a reference, then the spin of the neutrino (a left-handed particle) "looks" in the direction of a left-handed screw rotating clockwise along the particle path (Fig. 25). And the antineutrino is a right-handed particle. Its spin is directed along the movement of a right-handed screw advancing along the movement of the neutrino.

Incidentally, from this definition of the neutrino and antineutrino it follows directly that the rest mass of these particles is exactly zero. This can be proved by pure logic. Indeed, imagine that the neutrino has

a non-zero rest mass. According to the theory of relativity such a particle always moves slower than light. Thus, an observer moving close to this particle with a velocity exceeding that of the neutrino, but below the light velocity, would see the neutrino as receding from him. The particle impulse whose direction depends on the velocity of the observer relative to it, would be directed opposite to that of the spin. For an observer moving faster than the neutrino, the latter would turn into an antineutrino. The particle would change its nature depending on the position of the observer, its inherent properties would depend on the frame of reference. Here we have a contradiction, except when the mass of the neutrino and antineutrino is equal to zero. In this case the particle can move only with the velocity of light. For any observer a neutrino remains a left-handed particle, and antineutrino, a right-handed one.

The neutrino has a lot of work to do, it plays a very important role in the universe.

In addition to the neutrino that takes part in beta-disintegration together with the electron, there is another type of neutrino—the muon neutrino, which arises in the course of disintegration when a muon is born. The neutrino appearing together with a muon differs from the one appearing together with an electron.

For twenty years the neutrino had been faithfully serving science, but nobody had observed it in direct experiments. Its existence had been asserted on the basis of indirect data. Beginning with 1953, F. Reines and C. Cowan (USA) carried out several direct observations of neutrinos. The physical essence of their procedure can best be understood from the first and simplest experiment. Later measurements were more accurate and, of course, more complicated, but

they were based on the idea of the first experiment.

We know that a neutron disintegrates into a proton, an electron, and an antineutrino. Reines and Cowan assumed, and quite reasonably too, that a reverse reaction is also possible. The proton, absorbing the antineutrino, turns into a neutron after the emission of a positron. Both reactions can be written down as follows:

forward reaction—neutron disintegration

$$n \rightarrow p + e^- + \tilde{\nu}$$

reverse reaction—capture of the antineutrino by the proton

$$p + \tilde{\nu} \rightarrow n + e^+$$

But the proton mass is equal to 1836 em, and the neutron mass, to 1838.6 em, i.e. it is greater. We must also add the mass of the positron, 1 em. Thus the mass of the products of the reverse reaction exceeds that of the original proton by almost 4 em. Therefore a reverse reaction is only possible when the energy of the antineutrino is sufficiently high, about 2 MeV. The reaction is said to have an energy threshold of about 2 MeV (more precisely, 1.8 MeV). Consequently, if we use a very powerful source of antineutrinos containing particles of energies higher than 2 MeV to irradiate protons, then positrons and neutrons will appear from time to time. One source of antineutrinos as well as neutrinos is a nuclear reactor.

How do we register positrons and neutrons appearing in this reaction? The positron will immediately annihilate with one of the neighbouring electrons and will emit two gamma-quanta. When registering gamma-quanta of energies about 0.5 MeV it is possible

to register the appearance of positrons. In order to register neutrons, Reines and Cowan took advantage of the ability of cadmium to readily absorb neutrons. The absorption is accompanied by emission of gamma-quanta. But these quanta appear a few microseconds after the annihilation quanta. The point is that the neutron needs time to encounter the cadmium nucleus. Each step in the reaction of absorption of an antineutrino by a proton and of the formation of a positron and a neutron is thus accompanied by *two* flashes of gamma-quanta spaced a few microseconds. To register gamma-quanta, use was made of a liquid (scintillator) which glows when gamma-quanta penetrate it. Flashes of light were registered by photomultipliers, instruments receiving light impulses and amplifying the resultant electric signals. The two quanta resulting from annihilation produced the first flash, which was then followed by a flash from the quanta appearing on absorption of the neutron.

The set-up consisted of a tank 75 cm both in height and diameter containing a mixture of toluene with another hydrocarbon. This mixture was simultaneously a target (because it contained a great amount of hydrogen—protons) and a scintillator (since it produced flashes of light when gamma-quanta appeared in it). A cadmium compound was dissolved in the liquid. The tank walls were transparent, of course. The vessel was surrounded with a bank of 90 photomultipliers. The set-up was placed under a large nuclear reactor in Hanford and securely shielded from its radiation. The reactor not only produced antineutrinos, which could pierce practically any shielding, but also protected the set-up from cosmic radiation. Experiments were made with the reactor in operation and at a standstill. In the former case more flashes were observed, their number being used to calculate

the probability of disintegration of the proton under the effect of the antineutrinos. The first results were not accurate enough. Later on the procedure was improved. Cowan and Reines used three layers of a scintillating liquid enclosed in flat rectangular tanks. Two tanks with a target—an aqueous solution of cadmium chloride—were placed between three scientillator tanks. The number of photomultipliers was increased, shielding from external radiation was improved. The experiments were carried out on the Savannah River reactor. It is significant that the frequency of pair pulses from the antineutrino-proton reaction was about three counts per hour. As a result of these and subsequent experiments it was found that the probability of an antineutrino-proton reaction was about 11×10^{-44} cm^2. The probability of the reaction, or its cross section, is expressed in square centimetres, or rather in fractions of a square centimetre. We know that the proton radius is equal to 1.3×10^{-13} cm. Thus, its cross section is about 5×10^{-26} cm^2. But the antineutrino "sees" it as 11×10^{-44} cm^2. From this it follows that an overwhelming majority of antineutrinos dash through protons without slowing down, as if they were moving through a void, and only a negligible portion of the antineutrinos react. With such a low probability of reaction the neutrino pierces the earth and the sun practically without reacting with matter. In general, this particle reacts so seldom that on leaving the nucleus it wanders about in outer space. Its free path is greater than the diameter of the visible portion of the universe. Disintegration reactions yielding neutrinos and antineutrinos occur much more often than reactions of their absorption, therefore neutrinos accumulate in the universe. It would be interesting to know what this will lead to.

In considering the problem of weak interactions

the question arose whether neutrinos appearing in beta-disintegration are identical with those born together with muons. Some suspicions of their dissimilarity have already been voiced. A mu-meson disintegrates into an electron, a neutrino, and an antineutrino. Neutrinos and antineutrinos, being particles and antiparticles, may annihilate from time to time. So it would seem that there must be a reaction of disintegration of a muon into an electron and gamma-quanta. Such a reaction, however, has not been observed, although this disintegration involves electromagnetic processes. For instance, disintegration of a muon into an electron, a neutrino, an antineutrino, and gamma-quanta has been registered. It is natural to suppose that there is no annihilation because the neutrino and the antineutrino are of dissimilar nature. The antineutrino belongs to a different neutrino.

Late in 1959 Academician B.Pontecorvo proposed the use of high-energy proton accelerators in neutrino experiments. On collision of protons with nucleons, pi-mesons are born. Disintegration of high-energy pi-mesons into mu-mesons and neutrinos serves as a source of high-energy neutrinos. It should be noted that neutrino experiments are necessary not only for elucidating the difference between neutrinos of different origin, but they are extremely important for the theory of weak interactions in general.

A high-energy neutrino (of over 100 MeV) penetrating a nucleon may give birth to a mu-meson. If the mu-meson neutrino is identical with the electron neutrino, electrons will be born as well (recall the experiments of Reines and Cowan). If the neutrinos are dissimilar, no electrons will result.

In 1961-1962 the first neutrino experiment carried out in Brookhaven under the guidance of L.Lederman showed that the muon and electron neutrinos are

different particles. Therefore the relevant neutrino symbols are given different subscripts, ν_μ and ν_e. The reaction of disintegration of a negative mu-meson is now written thus:

$$\mu^- \rightarrow e^- + \tilde{\nu}_e + \nu_\mu$$

and that of a positive one,

$$\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$$

Along with the electron, an electron antineutrino and a muon neutrino are born. Together with the positron, there appear an electron neutrino and a muon antineutrino, since the positive muon is an antiparticle relative to the negative muon.

Now we will dwell briefly on the procedure of the neutrino experiment. A proton beam of energy 15 GeV directed at a beryllium target yielded an intensive flux of pi-mesons whose mean energy was about 3 GeV. The pions, freely traversing a 20-metre path, partly (by about 10%) disintegrated into mu-mesons and neutrinos. (A complete disintegration requires a path of about 150 m, but over such a length the beam diverges too strongly, and this is extremely disadvantageous.) Then the beam passed through a steel shield 13.5 m thick consisting of the armour of a scrapped battleship and was freed of muons, non-disintegrated pions, and in geneal of all particles except neutrinos. Getting into a 10-ton spark chamber, the neutrinos sometimes reacted with its material (aluminium) and yielded mu-mesons. No electrons resulted from the reaction. In other words, the reaction was

$$\nu_\mu + n = p + \mu^-$$

and there was no reaction

$$\nu_\mu + n = p + e^-$$

This served as proof of the difference between the muon and electron neutrinos.

The experiment lasted six months during which the synchrotron made about 2 mln pulses. Since each pulse took 3×10^{-6} sec, the net irradiation time was 6 sec. Incidentally, the pulsed operation of the accelerator made it possible to decrease the background due to cosmic muons. Cosmic neutrinos affected the set-up for only 6 sec. Nevertheless, 480 mu-mesons of cosmic origin were registered during operation. The great majority of these mesons were successfully separated from the muons of synchrotron origin. To this end, special equipment was used which enabled determining from what side the neutrinos giving birth to mu-mesons had come. Only those were taken into account which were born from the neutrinos arriving with the synchrotron beam.

During the experiment 10^{14} high-energy neutrinos entered the chamber. As a result of a thorough analysis of 5000 photos (they were made not at each pulse of the synchrotron, but only when a signal from the spark chamber indicated a reaction which might prove useful) 51 cases were selected where muons had unquestionably been born by a synchrotron neutrino. Of these, in 29 cases only a muon was born, while in 22 cases some other particle (a pion, etc.) appeared as well.

The spark chamber consisted of 90 aluminium plates of thickness 2.5 cm and surface area 0.44 m^2 grouped into ten stacks of nine plates each. The plates were spaced at 9 mm, the gaps between them being filled with neon. Upon a signal from an electronic device which detected ionization from a flying charged particle a high voltage was fed to the plate. Plus and minus voltage was supplied to each pair of adjacent plates. The high voltage caused sparks between the plates due to the muon which ionized the neon in flight.

Three-dimensional photos of particle tracks were taken through the transparent walls of the chamber.

In 1962, neutrino experiments were repeated at the CERN on a 28-GeV proton synchrotron. Magnetic focusing made it possible to obtain much denser neutrino beams. To register the birth of muons on neutrino-proton collisions use was made of a bubble chamber and a spark chamber. In all, 332 000 photos were made, including 277 000 in a neutrino beam (which resulted from disintegration of positive pions into positive muons and neutrinos) and 55 000 in an antineutrino beam formed on disintegration of negative pions.

The neutrino experiments at the CERN pursued several objectives. In the first place, they confirmed the conclusion that the muon and electron neutrinos are different particles. Besides, the scientists looked for the intermediate boson responsible for the weak interaction; we have already spoken of this boson. The idea of the search was as follows: the muon neutrino and the mu-meson formed on collision of the neutrino with the proton are weakly interacting particles, they do not take part in strong interactions. Therefore, if a weak interaction takes place with the aid of an intermediate boson, the latter should always be born in the given reaction. At low energies it may be merely virtual and not observable in the experiment. At high energies, however, it can be quite tangible. Then, having existed for the period assigned to it (it disintegrates semistrongly or semiweakly and lives supposedly for about 10^{-17} sec), it splits into two particles. This may be any one of the following pairs: $\mu^+\nu_\mu$, $e\nu_e$, $\pi\pi^0$, $K\pi^0$. Of special interest are disintegrations into K- and pi-mesons. Consequently, if we could detect the birth of a mu-meson upon a neutrino-proton collision and together with it the appearance of

another mu-meson or a pair of pi-mesons (a charged and a neutral one) this event could be considered as evidence of the existence of the intermediate boson. It is still necessary, of course, to prove that pi-mesons make up the particle which disintegrated some time after the birth of the mu-meson. But this can be done very well now, as will be seen from the section on resonance particles. Naturally, in order to prove the existence of the intermediate boson, a sufficient number of suitable events should be accumulated. As we have already mentioned, so far nobody has proved that the intermediate boson exists, although events which could be interpreted in favour of it have been observed. It has only been proved that if it exists its mass is not less than 1.3 GeV.

In the neutrino experiments at the CERN scientists also verified the law of conservation of the lepton charge at comparatively high lepton interaction energies. The weak (lepton) structure of the nucleon was studied. Finally, it was discovered that the cross section of an inelastic neutrino-nucleon interaction increased (which also means an increase in the probability of birth of muons) with a rise in the energy of a neutrino-nucleon collison. For neutrino energies exceeding 3 GeV a cross section of about 10^{-38} cm^2 was recorded. Recall that for an electron neutrino (an antineutrino) it is about 10^{-43} cm^2 at energies of $\sim$2 MeV.

MUONS

As noted above, the source of muons is disintegration of pi-mesons. They also result from disintegration of so-called *K*-mesons, or strange mesons. According to their mass the muons can be classed among the mesons, but in other respects they are electrons, heavy

electrons. Some kind of prohibition evidently prevents pi-mesons from disintegrating directly into electrons, and disintegration occurs through an intermediate stage, through an excited electron possessing an increased energy, i.e. a muon. The similarity between the muon and the electron is confirmed by the following: there are only a positive and a negative muons, there is no neutral one. The spin of the muon is 1/2, i.e. it is equal to that of the electron. The muon does not take part in nuclear (meson, or strong) interactions. The muon, together with the electron and the neutrino, obeys the law of conservation of leptons. The difference between the muon and the electron consists in the fact that the former has a mass 206.76 times higher than that of the electron. Besides, the muon is unstable, but it is highly probable that this is due to its high mass and excessive energy, it being excited, overburdened with energy. Situated on a high energy level, it gives off the excess energy, turning into an unexcited electron and two neutrinos. The principal qualitative difference between the muon and the electron is that the muon has a neutrino "of its own", a muon neutrino. It is not quite clear yet why nature has created the muon, and with its own neutrino to boot.

It is significant that the muon lifetime is determined from the lifetime of the positive mu-meson. The negative muon is assumed to have the same lifetime as the positive one, because, judging by all the other particles and from theoretical considerations, the lifetime of a particle is precisely equal to that of its antiparticle. The lifetime of the negative muon is very difficult to measure for the simple reason that when encountering an atom a muon penetrates it and settles, like an electron, in an orbit, replacing one of the atom's electrons.

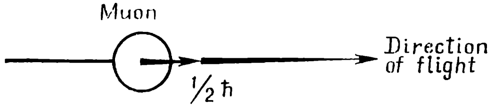

Fig. 26. The muon spin is equal to $1/2\ \hbar$ and is directed predominantly along the flight path of the muon.

Being located closer to the nucleus than the electron, the muon, with a certain degree of probability, is captured by the nucleus, its life ceases before natural disintegration. When a negative muon is absorbed by a nucleus, the number of leptons in the universe decreases by one. To compensate for the loss the nucleus emits a neutrino, and the original number of leptons is restored. The absorption of a negative muon hinders determination of its natural lifetime. By the way, a similar difficulty prevents the measurement of the lifetime of the negative pi-meson.

Since the mass of the muon is almost 207 times that of the electron while their charges are equal, the radius of the muon orbit about the nucleus is as many times less than the radius of the electron orbit. Penetrating the atomic electron shell, the muon shields off one of the charges of the nucleus, and therefore the outermost electron shell is rearranged in accordance with the new effective value of the nuclear charge. An atom in which one of the electrons has been displaced by a muon is called a mesic, or mesonic atom. The most accurate value of the muon mass has been obtained from the radiation spectrum of the mesic atom. A muon (as well as an electron) getting into an atom does not settle in the lowest orbit right away. It jumps over from one orbit to another, emitting X-rays. The energy of the emitted photons depends on the muon mass, it is as many times greater than the energy of the photons produced upon electron

transitions as the muon mass is greater than that of the electron. Investigating the radiation spectrum of the mesic atom one can determine the muon mass. But there are few mesic atoms, the intensity of their spectrum is negligible, and it cannot be studied thoroughly enough. In their attempts to overcome this difficulty the physicists resorted to a ruse. It is known that the absorption of radiation energy by an atom greatly increases in the energy range close to the boundary of the spectrum series, when the energy is equal to that necessary for removing an electron from the atom. Irradiating lead atoms with X-rays emitted from a mesic atom of phosphorus, scientists found, from the lead spectrum boundary, the energy of the X-rays of the mesic atom and calculated the most accurate value of its mass (206.76 ± 0.02 em).

We have already mentioned the deviation of the electron magnetic moment from the calculated value without taking into account the virtual processes. A similar deviation is observed in the value of the muon magnetic moment. The anomaly in the magnetic moment was calculated assuming the muon to be equivalent to the electron in every respect. Then, in extremely refined experiments, the experimental value of the anomaly was found. The agreement was exceptional. This proved convincingly the correctness of the notion of the muon as a heavy electron. Consequently, we can readily shift the muon into the lepton group and consider that we called it a meson by mistake. Scientists were a bit too overjoyed when Anderson and Neddermeyer discovered in 1936 a particle of mass equal to 200 electron masses and exactly identical to the one predicted by H.Yukawa the year before. Nature does sometimes play jokes with scientists and throws in something that seems just right at first glance. The true particle predicted by Yukawa—

the pi-meson—was discovered only 11 years later, in 1947, after a splendidly organized "round up" in which physicists of many countries took part. To everybody's delight the muon was discovered as well.

The Soviet academician Ya.Zeldovich found an interesting application for the muon, although it will hardly be of any practical value. Let us visualize mesic deuterium. A negative muon rotates around a deuton at a close distance. The mesic deuterium nucleus is practically electrically neutral because of the small radius of the orbit of the muon, which spends some time inside the nucleus ("hops" in and out). The nucleus allows the deuton to approach it in spite of its electric charge. A thermonuclear reaction at a low temperature becomes possible in principle.

Individual steps of such a reaction have been observed experimentally. If the muon lived long enough, did not disintegrate and was not captured by nuclei, one muon could catalyze many steps of a thermonuclear reaction and the process would acquire practical importance.

A positive mu-meson can form, together with an electron, a kind of an atom, a muonium (mu-mesonium). In the muonium an electron rotates about a positive muon as it rotates about the proton in the hydrogen atom. The muonium was first synthesized in 1960. To obtain it, positive muons were injected into a stainless-steel tank filled with pure argon up to a pressure of 50 atm. It was found that *each* muon entering the tank yielded a muonium. Its existence was ascertained by measuring the polarization—a definite orientation of the muon spin in space—before and after the muons got into the argon. In the argon, the muons, which had formerly been polarized, lost their polarization, they became depolarized. Normally, a muonium is in the $1^2s_{1/2}$-state.

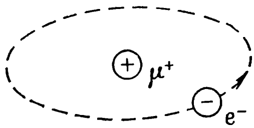

Fig. 27. Muonium. A negative electron rotates about a positive muon, as it rotates about the proton in the hydrogen atom.

Later a very refined muonium experiment was carried out. In 1962 the hyperfine structure, or hyperfine splitting, of the muonium spectral line was measured. Due to the different orientation of the electron spin relative to the muon spin (two such orientations are possible: parallel and antiparallel) in the lower energy state, the energy or frequency of the light emitted by the muonium upon transfer of the electron from an upper energy level to the lowest one may acquire one of two slightly differing values. This phenomenon is termed the hyperfine structure, or hyperfine splitting of levels. The experiment produced, for the muonium, hyperfine splitting precisely coinciding with the one calculated assuming that the muon is a heavy electron. The experiment confirmed once more that muons are heavy electrons.

Let us now revert to Table 2. It contains only one complete group of known particles, the lepton group. The other groups are incomplete. There exist, for instance, K-mesons which do not figure in the Table. Heavy particles—nucleons—constitute part of the more general class of baryons. Besides the nucleons, the baryons include the hyperons, which are heavier than nucleons. They differ from nucleons in that they are strange particles. Strangeness is denoted by a figure. It may be equal to zero, unity, minus two.

In everyday life it is not usual to denote strangeness by figures. The introduction of the term "strangeness" was evidently caused by the physicists' inclination towards unusual terminology. True, in each individual case terms are chosen for some reason or other. The properties of strange particles greatly surprise all scientists. In the first place, nobody ever expected them to exist at all. The appearance of strange particles dealt a heavy blow on the self-conceitedness of the physicists. It appeared that everything could not be predicted in nature as they were beginning to think at the time. The appearance of strange particles proved once more the leading role of experiment in science.

Incidentally, the negative muon is sometimes assigned a strangeness of -1, while the positive muon, $+1$.

We will now give you a respite by devoting several of the following sections to simpler and more familiar phenomena. We will deal with the properties of atoms and nuclei as "assemblies" of many particles. This is how we see them in practice. Certain particles are familiar only to physicists. Those readers who are not interested in or are sufficiently familiar with phenomena occurring in complex atoms may skip a few pages and continue their reading with the section "Complete List of Elementary Particles".

Electron Shells

For a better understanding of the structure of electron shells in complex atoms we will recall the system of quantum numbers for hydrogen applicable to atoms with a small number of electrons. The principal quantum number n characterizes the number of

a shell. For the first shell it is equal to 1, for the second 2, and so on. The orbital quantum number l characterizes the magnitude of the orbital momentum of an electron in $\hbar$ units. The maximum value of the orbital quantum number is lower by unity than the principal number. Besides the maximum value, the orbital momentum can take on all integral values from the maximum to zero. The states with orbital momenta equal to 0, 1, 2, 3, etc., are denoted by the small letters s, p, d, f, and so on, respectively. The magnetic quantum number m corresponds to the projection of the orbital momentum onto a certain arbitrary direction. The projection can assume all integral values from l to $-l$. The spin quantum number m_z can assume one of two values in accordance with the two orientations of the spin relative to the orbital momentum, and, if the latter is zero (the s-state), relative to the nuclear spin. One value of the spin number differs from the other by unity, of course. With a small number of electrons in the atom, it is the orbital momentum that orients itself with respect to the external magnetic field. The connection between the external field and the orbital momentum turns out to be stronger than that between the orbital and spin momenta.

In atoms with a great number of electrons the system of quantum numbers differs slightly from that for the hydrogen atom; namely, the orbital momentum adds up with the spin momentum to form the total angular momentum of the electron, and this total momentum assumes different orientations relative to the external field. The orbital and spin momenta are strongly interdependent in this case. In line with the aforesaid the state of the electron in the atom is characterized by the following quantum numbers: the principal quantum number n, the orbital quantum

number l, the total angular momentum j, and the projection of the total momentum onto a certain direction, m. We say "a certain direction" because an external magnetic field may have any direction. Therefore, no matter onto which direction the total momentum is projected, its projection can only assume values differing by unity. Its maximum value may be j, minimum, $-j$. In the absence of an external magnetic field levels with different magnetic quantum numbers coincide, they degenerate, but the number of possible states of the electrons in the atom still does not decrease.

Let a single electron reside in one of the shells. In the *s*-state the orbital momentum is equal to zero. Therefore, in the *s*-state the total momentum is equal to the proper (spin) momentum, i.e. 1/2. In the absence of an orbital momentum the projection of the total momentum onto the direction of the external magnetic field can assume only one of two values, +1/2 and −1/2. The total number of possible states of an electron is then equal to two. In the *p*-state, when the orbital momentum is equal to unity, the total momentum can assume one of two values: 1/2 if the spin is antiparallel to the orbital momentum, and 3/2 when it is parallel. Accordingly, the projection of the total angular momentum onto the direction of the external field can assume one of two values, 1/2 and −1/2, when the total momentum is 1/2; and 3/2, 1/2, −1/2, and 3/2 if the total momentum is 3/2. Consequently, if the total number of levels is equal to two in the *s*-state, it reaches six in the *p*-state. It is easy to calculate the number of possible combinations for the other states; for the *d*-state for instance, it is equal to ten.

The system of levels, or, more precisely, states, or terms, of an atom having several electrons is built

similarly to the system of levels for one electron. The only difference is that here the spin is the vector sum of the spins of all s-electrons. The total orbital momentum is the vector sum of the orbital momenta of all the electrons, it is denoted by the letter L. The total spin momentum and the total orbital momentum add up and yield the total angular momentum for all the electrons J. The total momentum takes on any values from $L+S$ to $L-S$. The projection of each value of the total angular momentum takes on all integral values from J to $-J$.

When there are many electrons and part of them are excited, the system of levels presents a rather complicated picture, and the spectrum of complex electron shells has an involved structure. We will not dwell on all these niceties, but will consider the procedure of tabulating elements in the normal, unexcited state. We can use as a basis the possible states of a lone electron. Table 3 (borrowed from *The Reference Book for an Experimenter Physicist* by D.Kay and T.Labby) lists the possible states for four values of the principal quantum number n.

Each period in the Mendeleyev Table of the Elements begins with the filling of a new shell.

Hydrogen is the first element of the first period. The first shell may contain one more electron. The element with two electrons in the 1s-state is helium. This is the final element of the first period, which contains two atoms. An atom with a filled shell is one of a noble gas. It can be seen from Table 3 that the second shell (principal quantum number 2) can accommodate eight electrons, it has eight possible states. The first electron, finding itself in the 2s-state, forms lithium, an analogue of hydrogen. The filling of subsequent levels yields elements of the second period of the Mendeleyev System which ends with

TABLE 3
POSSIBLE STATES OF ONE-ELECTRON SYSTEM

Principal quantum number n	1	2			3					4						
Orbital angular momentum l	0	0	1	1	0	1	1	2	2	0	1	1	2	2	3	3
Total angular momentum j	1/2	1/2	1/2	3/2	1/2	1/2	3/2	3/2	5/2	1/2	1/2	3/2	3/2	5/2	5/2	7/2
Magnetic quantum number m	+1/2 to −1/2	From +1/2 to −1/2	+1/2 to −1/2	+3/2 to −3/2	From +1/2 to −1/2	+1/2 to −1/2	+3/2 to −3/2	+3/2 to −3/2	+5/2 to −5/2	From +1/2 to −1/2	+1/2 to −1/2	+3/2 to −3/2	+3/2 to −3/2	+5/2 to −5/2	+5/2 to −5/2	+7/2 to −7/2
Number of states	2	2	2	4	2	2	4	4	6	2	2	4	4	6	6	8
Total number of states	2	8			18					32						
Shell	*K*	*L*			*M*					*N*						
Subgroup		I	II	III	I	II	III	IV	V	I	II	III	IV	V	VI	VII

neon, a noble gas. Neon has only ten electrons: two in the first shell and eight in the second. The element with one of the electrons in the third shell, in the *s*-state, also belongs to analogues of hydrogen; it is sodium, an alkali metal.

Deviations from the simple rule begin with the third shell. It will now be useful to turn to Table 4, from which we can see the distribution of electrons over the shells with different principal quantum numbers.

Upon filling of the *s*- and *p*-state levels in the third shell the electrons begin to settle in the fourth shell, although the third shell has vacancies; true, these vacancies have a higher orbital momentum, they are 3*d*-states. In all, the third shell has 18 states. Among these there are two *s*-states, six *p*-states and ten *d*-states. But the electrons dislike the *d*-state, they prefer to rise to a higher level, so that they could settle in the more comfortable *s*-state or, as a last resort, in the *p*-state. The third period ends with argon. The fourth begins with potassium, also an alkali metal. Then, a whole period exhibits parallel, more precisely, interchangeable filling of the *s*- and *p*-levels in the fourth shell and the *d*-levels in the third shell. When the *s*- and *p*-levels in the fourth shell have been filled the electrons again prefer to settle on the *s*- and *p*-levels, now in the fifth shell. True enough, this occurs after all the *d*-levels in the third shell have been filled. But in the fourth shell there are the *d*- and *f*-levels as well. Lots of vacancies are available, only eight sites out of 32 are filled in the fourth shell, and the electrons hurry to reach a higher shell. They hate staying in the *d*- and *f*-states.

The chemical properties of the elements depend on the outermost electrons. In the sixth period (see Table 4) an interesting phenomenon is observed. Begin-

TABLE 4

DISTRIBUTION OF ELECTRONS OVER ORBITS CHARACTERIZED BY PRINCIPAL QUANTUM NUMBER n

n	1	2	3	4
Period 1				
1 H	1			
2 He	2			
Period 2				
3 Li	2	1		
4 Be	2	2		
5 B	2	3		
6 C	2	4		
7 N	2	5		
8 O	2	6		
9 F	2	7		
10 Ne	2	8		
Period 3				
11 Na	2	8	1	
12 Mg	2	8	2	
13 Al	2	8	3	
14 Si	2	8	4	
15 P	2	8	5	
16 S	2	8	6	
17 Cl	2	8	7	
18 Ar	2	8	8	
Period 4				
19 K	2	8	8	1
20 Ca	2	8	8	2
21 Sc	2	8	9	2
22 Ti	2	8	10	2
23 V	2	8	11	2
24 Cr	2	8	13	1
25 Mn	2	8	13	2
26 Fe	2	8	14	2
27 Co	2	8	15	2
28 Ni	2	8	16	2
29 Cu	2	8	18	1
30 Zn	2	8	18	2
31 Ga	2	8	18	3
32 Ge	2	8	18	4

Continued

n	1	2	3	4	5	6
Period 4						
33 As	2	8	18	5		
34 Se	2	8	18	6		
35 Br	2	8	18	7		
36 Kr	2	8	18	8		
Period 5						
37 Rb	2	8	18	8	1	
38 Sr	2	8	18	8	2	
39 Y	2	8	18	9	2	
40 Zr	2	8	18	10	2	
41 Nb	2	8	18	12	1	
42 Mo	2	8	18	13	1	
43 Tc	2	8	18	13	2	
44 Ru	2	8	18	15	1	
45 Rh	2	8	18	16	1	
46 Pd	2	8	18	18		
47 Ag	2	8	18	18	1	
48 Cd	2	8	18	18	2	
49 In	2	8	18	18	3	
50 Sn	2	8	18	18	4	
51 Sb	2	8	18	18	5	
52 Te	2	8	18	18	6	
53 I	2	8	18	18	7	
54 Xe	2	8	18	18	8	
Period 6						
55 Cs	2	8	18	18	8	1
56 Ba	2	8	18	18	8	2
57 La	2	8	18	18	9	2
58 Ce	2	8	18	20	8	2
59 Pr	2	8	18	21	8	2
60 Nd	2	8	18	22	8	2
61 Pm	2	8	18	23	8	2
62 Sm	2	8	18	24	8	2
63 Eu	2	8	18	25	8	2
64 Gd	2	8	18	25	9	2
65 Tb	2	8	18	27	8	2
66 Dy	2	8	18	28	8	2
67 Ho	2	8	18	29	8	2

Continued

n	1	2	3	4	5	6	7
Period 6							
68 Er	2	8	18	30	8	2	
69 Tm	2	8	18	31	8	2	
70 Yb	2	8	18	32	8	2	
71 Lu	2	8	18	32	9	2	
72 Hf	2	8	18	32	10	2	
73 Ta	2	8	18	32	11	2	
74 W	2	8	18	32	12	2	
75 Re	2	8	18	32	13	2	
	2	8	18	32	14	1	
76 Os	2	8	18	32	14	2	
	2	8	18	32	15	1	
77 Ir	2	8	18	32	15	2	
	2	8	13	32	16	1	
78 Pt	2	8	18	32	17	1	
	2	8	18	32	18		
79 Au	2	8	18	32	18	1	
80 Hg	2	8	18	32	18	2	
81 Tl	2	8	18	32	18	3	
82 Pb	2	8	18	32	18	4	
83 Bi	2	8	18	32	18	5	
84 Po	2	8	18	32	18	6	
85 At	2	8	18	32	18	7	
86 Rn	2	8	18	32	18	8	
Period 7							
87 Fr	2	8	18	32	18	8	1
88 Ra	2	8	18	32	18	8	2
89 Ac	2	8	18	32	18	9	2
90 Th	2	8	18	32	18	10	2
91 Pa	2	8	18	32	20	9	2
92 U	2	8	18	32	21	9	2
93 Np	2	8	18	32	23	8	2
94 Pu	2	8	18	32	24	8	2
95 Am	2	8	18	32	25	8	2
96 Cm	2	8	18	32	25	9	2
97 Bk	2	8	18	32	27	8	2
98 Cf	2	8	18	32	28	8	2
99 Es	2	8	18	32	29	8	2
100 Fm	2	8	18	32	30	8	2

Continued

n	1	2	3	4	5	6	7
Period 7							
101 Md	2	8	18	32	31	8	2
102 (No)	2	8	18	32	32	8	2
103 Lr	2	8	18	32	32	9	2
104 Ku	2	8	18	32	32	10	2

ning with lanthanum and ending with lutecium fifteen elements have two absolutely identical outermost shells (principal quantum numbers 5 and 6); exceptions are lutecium and gadolinium which have 9, not 8, electrons in the shell with the principal quantum number 5. Each of the subsequent elements in this group is formed as a result of the filling of the long vacant *d*- and *p*-levels in the fourth shell. But the fourth shell is far away from the outermost layers. Therefore, when there are electrons in the fifth and sixth shells and the *s*-level in the sixth shell is filled completely, the filling of the fourth shell will hardly affect the chemical properties of the elements. Thus the whole group occupies a single box in the Table, where the elements are lumped together under the name of lanthanides, or rare earths.

D. Mendeleyev possessed an amazing ability for generalization and constructed the Periodic System of the Elements solely on the basis of their chemical properties. Mind you, in Mendeleyev's time nothing was known about quantum numbers, energy levels, and similar concepts of present-day science.

Any electron in any element can be raised to a higher unoccupied level by giving it the necessary amount of energy. A reverse transition will cause emission of an energy quantum (a photon). If an electron

has been torn away from one of the lower levels, a reverse transition will result in emission of an X-ray photon of high energy and frequency. The most penetrating X-rays are produced on transition from upper shells to the lowest, K-shell. Transitions between upper levels lead to emission of visible light or photons with a frequency close to the visible spectrum.

There are several selection rules for transition of electrons from lower to upper levels and vice versa. These rules are derived by quantum mechanics from a rigorous analysis of probability of one transition or another. Here, we will adduce only one, the most important, rule and will try to interpret it physically.

Electron transitions are possible if the orbital momentum changes by ± 1 ($\Delta L = \pm 1$), while the total angular momentum (the sum of the orbital and spin momenta) also changes by ± 1 or does not change at all. Transitions with a change of more than ± 1 in the orbital and total momenta and also transitions without a change in the orbital momentum are forbidden.

The quantum prohibition becomes clear if one recalls that the photon angular momentum is equal to unity and that on birth or absorption of a photon the law of conservation of angular momentum should be obeyed, as it is in other reactions.

At the moment of leaving the atom the photon, whose spin is unity, can orient its spin parallel, antiparallel, and perpendicular relative to the total angular momentum of the atom in the final state. If the photon spin is parallel to the momentum of the final atom, then, according to the law of conservation of angular momentum, the total momentum in the final state should be one unit less than the momentum in the initial state due to the reduction in the

orbital momentum by unity on photon emission. With an antiparallel orientation of the photon spin relative to the momentum in the final state the total and orbital momenta in the final state should exceed by unity the momenta in the initial state for the same reason. Finally, when the photon spin is perpendicular to the momentum in the final state the total momentum should not change on photon emission. But the orbital momentum reduces by unity, since the formation of a photon requires expending a momentum equal to unity. But, despite the reduction in orbital momentum, the total momentum remains unchanged because in the course of emission the electron spin shifts from the antiparallel position to a parallel one. Therefore the total momentum increases by unity, and this compensates for the reduction in the orbital momentum, which makes part of the total momentum.

The selection rules do not imply absolute prohibitions. We have already dealt with the radio emission of hydrogen, when the orbital momentum remains unchanged. The photon acquires an angular momentum due to spin reorientation. But this process occurs very seldom, the emission time (the time of remaining in the "uncomfortable" position) exceeds ten million years.

Quantum Amplifiers (Masers and Lasers)

Quantum amplifiers and generators were discovered in 1954 by Soviet scientists Academicians N.Basov and A.Prokhorov, who were awarded the Lenin Prize for this work. In the same year J.Gordon, H.Zeiger,

and C.Townes* of Columbia University (USA) independently built a quantum amplifier which did not differ in its principle from that proposed by Basov and Prokhorov. Since then the number of investigations on quantum amplifiers has been growing like a snowball, and now we can say that a new science has been born, quantum radiophysics.

The most attractive feature of quantum amplifiers is the exceedingly low level of ambient noises and the possibility of amplifying not only very short radio waves, but also light waves. The Americans, as well as the Soviets, like to use abbreviations; in the USA quantum amplifiers of radiowaves are abbreviated as masers (microwave amplification by stimulated emission of radiation), and amplifiers of light waves, as lasers (light-assisted amplification by stimulated emission of radiation).

It is very difficult to expound an entire science on several pages, and therefore we will only give you a general physical notion of the operation of quantum amplifiers. Let us imagine two electron energy levels. We already know that by irradiating atoms with photons whose energy is precisely equal to that necessary for shifting an atom from a lower to a higher level we raise electrons from the lower to the upper level. Is it possible to shift *all* electrons in *all* atoms subjected to irradiation from a lower to an upper level? Not really. The point is that a photon settling on an electron residing on an upper level pushes it downwards, to a lower level, and the atom emits a photon. This phenomenon, which was predicted by Einstein in 1917, is called induced radiation. It is interesting and extremely significant that the two photons, or

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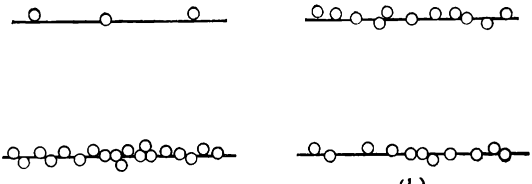
* Basov, Prokhorov and Townes received the Nobel Prize in physics for 1964 for these investigations.

waves emitted by the atom in induced radiation, are in phase, in other words they are coherent. Besides induced radiation there exists, of course, spontaneous radiation: electrons raised to a higher level spontaneously drop to a lower level. This process, however, occurs relatively slowly, and if the intensity of external irradiation is high enough, spontaneous radiation is neglected.

Induced radiation occurs with the same degree of probability as excitation. Therefore, some time after the beginning of irradiation half of the atoms in the irradiated space find themselves in an excited state, while the other half are at a lower energy level. As many electrons are pushed down from an upper level as rise from a lower to an upper level. Thus a dynamic balance is established, and no amplification is achieved. Indeed, amplification is possible only when few photons (e.g. a single one) are injected into the amplifier, while many are obtained at the output.

Amplification can be achieved if there is a possibility of collecting all excited atoms very rapidly in an isolated space, separating them from the unexcited atoms. Then a photon, finding itself exclusively among excited atoms, would push one electron down from the upper level. Two photons would result. The two photons would push two more electrons down from the upper orbits, and four photons would result. These would give birth to eight, and so on. We would have progressive amplification of radiation (a chain process) until half of the atoms have moved to the lower energy state. Then amplification would cease, because from this moment on the number of induced transitions from an upper to a lower level would be equal to the number of excitations, i.e. transitions from the lower to the upper level. The chain process (avalanche formation) is hindered by the emission of pho-



(a) (b)

Fig. 28. Distribution of electrons over energy levels:
(a)—in the equilibrium state; (b)—with intensive irradiation by photons of energy equal to the difference between level energies.

tons through the walls, which breaks up the chains. Therefore the walls should reflect the photons like a mirror. Then the photons will return into the space and the avalanche will continue to develop.

Quantum amplifiers of this type have been constructed, they are called two-level amplifiers, since they employ two energy levels. In practice, in order to build such amplifiers an ammonia molecule is used instead of atoms in which an electron is excited. This molecule contains three hydrogen atoms located in one and the same plane which makes the base of a triangular pyramid with a nitrogen atom at the apex. In the ammonium molecule the hydrogen atoms can rotate about an axis passing through the apex and the centre of the pyramid base. This rotation is quantized: the angular momentum takes on values multiple of $\hbar$. During rotation the hydrogen atoms move apart because of the centrifugal force. The faster the hydrogen atoms rotate and the higher the angular momentum, the greater is the separation between the atoms. At the same time the nitrogen atom oscillates relative to the plane in which the hydrogen atoms are rotating. Oscillations when the nitrogen atom crosses the plane

in which the hydrogen atoms are situated are called inversion oscillations, they are also quantized. The frequency of inversion oscillations is different for different angular momenta of the hydrogen atoms. The greater the angular momentum, the farther the hydrogen atoms are spaced from each other and from the nitrogen atom. The bond between them is weaker, and the oscillation frequency is lower, the quantum causing them being smaller.

For one of the values of the angular momentum ($3\,\hbar$) the frequency of inversion oscillations of hydrogen is 23 870.14 MHz. This frequency is used as carrier frequency and simultaneously as frequency being amplified.

Ammonia molecules are released from an "oven" where they are heated to 300 °K, i.e. approximately to room temperature. All kinds of oscillations are excited in them, among which there are many useful ones. Then the beam is passed through a non-uniform electric field (a quadrupole lens), which singles out the molecules in the required excited energy state. These molecules are not only separated from the unnecessary ones, but are also focused and find their way into a resonator tuned to the oscillation frequency of 23 870.14 MHz, where induced transitions from an upper to a lower level take place. The resonator produces a signal of indicated frequency, which corresponds to a wavelength of about 12.55 mm.

Quantum amplifiers of the type described are also called molecular amplifiers because the radiowaves are emitted by ammonia molecules, they are also referred to as beam amplifiers, as radiowaves are emitted by a beam of molecules. Strictly speaking, ammonia amplifiers are not used as amplifiers, because they have a number of drawbacks of which the most serious one is the fact that they can work only on one

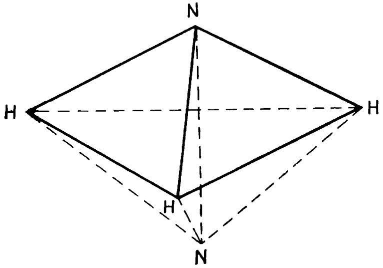


Fig. 29 Inversion oscillations. In the ammonia molecule (NH_3) the nitrogen atom may oscillate, crossing the plane in which the hydrogen atoms are situated. The frequency of these oscillations, which are called inversion oscillations, depends on the rotation momentum of the molecule about the axis along which the nitrogen atom oscillates. Quantum oscillators use the frequency of 23 870.14 MHz, which sets up at a rotation momentum of $3\hbar$.

frequency. Ammonia quantum amplifiers are employed as standard frequency oscillators, therefore the term "quantum oscillator" is more suitable.

Besides two-level quantum amplifiers there are three-level ones, which are used more widely and have also been proposed by Basov and Prokhorov.

Suppose there is one more, a third, level between the two quantum levels of which we spoke above. We will excite the highest energy level, transferring to it particles from the lowest one. To this end a substance is irradiated with quanta of energy equal to the energy of transition from the lowest to the highest level. We will obtain the same number of particles in two extreme states, the highest and the lowest, taking into account induced radiation from the upper to the lower level. Two cases are possible then, both of them of practical importance. Imagine that the particles shift reluctantly from the upper level to the

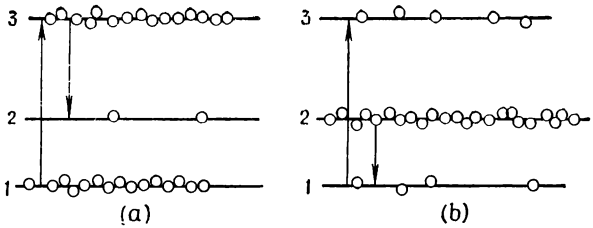


Fig. 30. Operation of three-level quantum amplifiers (schematic). In both cases *(a)* and *(b)* energy is supplied to raise the ions from level 1 to level 3. In *(a)*, level 3 is "overpopulated" compared with level 2; the frequency corresponding to transition from 3 to 2 is increased. In *(b)*, the ions shift spontaneously from 3 to 2. Level 2 is overpopulated compared with level 1, the frequency corresponding to transition from 2 to 1 increases.

middle (third) one and the probability of spontaneous transition is low. Then there will be many particles on the upper level as compared to the middle one. We can take advantage of this. Injecting quanta of different frequency whose energy is equal to that of transition from the upper to the middle level, we will obtain induced radiation from the upper to the middle level, or amplification of the signal, until the "population density" of the upper and middle levels become equal. In a three-level amplifier the energy of the illumination quanta is higher than that of the amplified quanta.

But there is another possibility: while we are "pumping" particles from the lower to the upper energy level, irradiating them with an illumination wave, they shift spontaneously from the upper to the middle level. This occurs when the time of spontaneous transition from the upper to the middle level is short as compared to the delay time of the signal to be ampli-

fied. The particles shift and accumulate on the middle level. They drop from the middle to the lower level, of course, but then illumination tosses them up to the upper level again. Gradually, an ever-decreasing number of particles remains to be shared between the upper and lower levels. They "drop out of the game", settling on the middle level. If the illumination source is very powerful, most of the particles can in general be "pumped" to the middle level. There will be many more particles on the middle level than on the lower one. In this case, injecting a weak signal coinciding in energy and frequency with transition from the lower to the middle level will induce transitions from the middle to the lower level and amplify the signal coinciding in frequency of transition between the lower and the middle levels. In the latter case it would be helpful if the distance between the lower and the middle levels were considerably smaller than that from the middle to the upper level. Then it would be easier to overpopulate the middle level. In general, the lower the level, the denser the population.

The resonator containing the substance should be tuned both to the illumination (auxiliary) wave and to the one to be amplified.

Such is the general principle of operation of a three-level quantum amplifier. But its practical realization is still a long way off. There are several methods for choosing the three levels. We also know three different methods of "illumination"—transfer of particles from a lower to an upper energy state.

Here, we will restrict ourselves to a brief description of a three-level amplifier where different orientations of the electron spin are used as energy levels.

For a three-level quantum amplifier a crystal is chosen which possesses a number of useful properties. We will not discuss them here, but will mention that

the ions interspersing the crystal lattice should be so located that their spins are more or less randomly directed. The nuclear spin of an ion should not be large, otherwise the interaction of the nuclear and electron moments will spread out the energy levels of the electron which are due to its spin. Precisely these levels are used in three-level quantum amplifiers.

In practice, use is made of crystals containing triply ionized atoms (ions) of chromium $Cr^{3+}(Z=24)$, iron Fe^{3+} $(Z=26)$, gadolinium Gd^{3+} $(Z=64)$ and some others.

Crystals of synthetic ruby find the widest application. This is an aluminium oxide (Al_2O_3) whose lattice is interspersed with chromium atoms. The chromium absorbs yellow, green, and violet colours. Therefore red light passes through the crystal. Hence the famous red colour of ruby. The more chromium the crystal contains, the darker is the ruby. In one of the quantum radiowave amplifiers which is described in the literature and will be discussed below use is made of a light-red ruby containing about 0.1% chromium with relation to the aluminium.

The triply ionized chromium atom has three electrons in the $3d$-shell. When the ruby is placed in a magnetic field its spin levels split in accordance with the possible values of the projection of the spin onto the direction of the magnetic field. In the magnetic field the chrome ion will then have several energy levels of which three are used for the three-level quantum amplifier. We will recall that part of the ions will have an energy corresponding to the lowest of the three selected levels, another part, to the upper, and the rest, to the middle level. By turning the spin in the magnetic field one can transfer ions from one energy state to another. We must transfer a maxi-

mum number of chromium atoms from the lower to the upper state. To this end, use is made of an alternating magnetic field whose frequency coincides with that required for this transfer. This is the resonance frequency.

In 1945 the Lenin Prize winner Soviet Academician E. Zavoisky discovered electron paramagnetic resonance (EPR); resonance absorption of energy of an alternating magnetic field by certain (paramagnetic) substances for reorientation of electron spins. This phenomenon is used in certain quantum amplifiers for pumping ions from a lower energy spin state to a higher one. The energy difference for two spin orientations is equal to the energy of the wave quantum, $h\nu$. Such amplifiers are therefore sometimes called paramagnetic amplifiers. Besides electron paramagnetic resonance, there is nuclear paramagnetic resonance (NPR), which was discovered soon after EPR. This is absorption of the corresponding frequency of an alternating electromagnetic field by nuclear magnets.

One of the ruby paramagnetic amplifiers described in foreign literature uses an excitation (or auxiliary) frequency of 24,200 MHz. The frequency amplified is naturally lower, it is equal to 9220 MHz, which approximately corresponds to a wavelength of 3 cm.

The background, or noise, in a quantum amplifier is caused by spontaneous transitions from upper to lower levels, by temperature fluctuations in the crystal lattice, and by radiation from the resonator walls. The latter two factors are the most powerful sources of noises, they depend on the temperature of the crystal and the resonator. To reduce the noises, the crystal is placed together with the resonator into liquid helium, where they are cooled down to the lowest temperature available in technological devices.

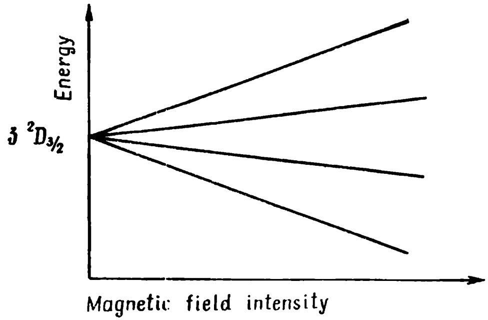


Fig. 31. Splitting of the $3^2D_{3/2}$ level in the external magnetic field. A rise in field intensity increases the differences in energies between the sublevels corresponding to different orientations of the total ion momentum in the magnetic field. When splitting two levels in a controlled magnetic field (only one level is shown) three sublevels are selected and used in a quantum paramagnetic amplifier. Such an amplifier can operate in accordance with a preassigned field intensity on different wavelengths.

By changing the permanent magnetic field it is possible to move energy levels apart and bring them closer together, thereby changing the frequency of the wave amplified. This is a great advantage of three-level amplifiers with a magnetic field. By varying the magnetic field intensity one can "scan" the space over a rather wide range of millimetre and centimetre waves. Quantum amplifiers are mainly used for special purposes, such as radioastronomy, paramagnetic resonance studies, communication systems based on scattering of radiowaves, radar systems, and tracking of satellites.

Ruby crystals are also used to obtain very strong flashes of coherent light rays. In *Scientific American* (No. 6, 1961) A. Shavlov describes an oscillator using

a dark-red ruby with a chromium content exceeding by about 10 times that of the oscillator mentioned above.

A cylindrical ruby crystal of about 4 cm long and 0.5 cm in diameter, whose end faces are strictly plane-parallel, optically polished and silver-plated (one is a perfect mirror and the other is translucent), is placed in liquid nitrogen and serves as a source of coherent radiation. The crystal is irradiated by a very powerful light source, i.e. a pulse lamp. The light "raises" the electrons to the upper energy level, i.e. excites them. The ruby begins emitting light. Quanta emitted at an angle to the axis of the crystal leave it and are lost. Quanta propagating along the axis induce coherent radiation on their way and on being reflected from the mirror end face, continue to do so. The light escapes through the translucent base as a parallel beam of intensity reaching 10 kW. The beam diverges very slightly, its angle is about 0.5 deg. If we direct this beam at the moon without the use of an optical system, it will produce a spot of diameter 400 km on the surface of the moon. By using an optical system we can reduce the spot diameter to 3 km. A beam issuing from a quantum optical amplifier can be focused into a point of diameter about 0.1 mm with the aid of a lense. Then the energy density may reach 100 kW per square centimetre.

CO_2 Laser

The early lasers, which were first discovered in 1961, used a neon-helium mixture. High-energy levels were excited by illumination from a powerful optical source. Soon afterwards several types of gas lasers were discovered of which the most promising was the

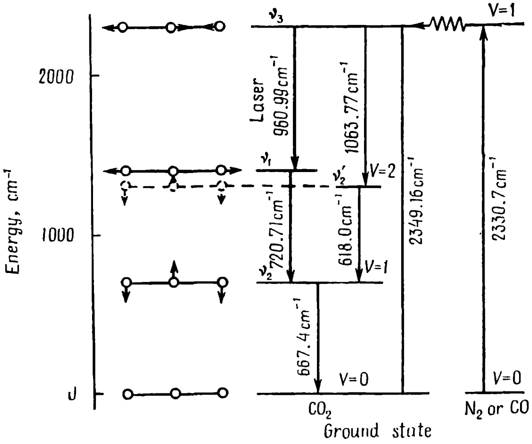


Fig. 32. Oscillation levels of
a CO_2 laser (schematic)

gas laser on carbon dioxide invented in 1964 (see *Uspekhi fizicheskikh nauk*, 91, No. 3, 1967).

After two years of improvement the efficiency of the CO_2 laser reached about 10%, the output in continuous operation being several hundred watts, while the efficiency of the best gas lasers of other types does not even reach 1% with the output lower by two orders.

The CO_2 laser uses a mixture of carbon dioxide with a predominant amount of nitrogen or a mixture of carbon dioxide and nitrogen with large additions of helium, at pressures of 5 to 10 mm Hg in a gas-discharge tube 20 to 70 mm in diameter and 1 to 6 m long. Mirrors, one of which is translucent, are placed on the end-faces of the tube, as in any other laser. The gas discharge in the tube is caused by a direct or alternating current from a 15 kW source.

The CO_2 laser utilizes an interesting method for overpopulating the upper oscillation level. The right-hand part of Figure 32 shows three types of basic oscillations of a CO_2 molecule at a quantum number 1. The upper one, ν_3, represents linear non-symmetric, the middle one, ν_1, linear symmetric, and the lower one, ν_2, deformation oscillation. The amount of energy of deformation oscillation is not great, and the figure also shows the deformation level of oscillations with a quantum number 2, which is close in energy to the symmetric linear oscillation level with a quantum number 1. The left-hand part of the figure represents the respective energy levels and energies of transition between them expressed in *wave numbers* (the wave number, which is measured in cm^{-1}, is the number of wavelengths contained in 1 cm). To convert wave numbers to the familiar energy units, the wave number should be multiplied by the Planck constant and by the light velocity. To obtain the laser effect it is necessary to overpopulate the ν_3-level as compared with ν_1 and ν_2' $(v=2)$, or the ν_1- and ν_2'-levels as compared with ν_2, or the ν_2-level as compared with the initial oscillation-unexcited states. In practice, the laser effect is observed with all indicated transitions, but it is most pronounced on transition from the ν_3-level to the ν_1- and ν_2'-levels.

The mechanism of operation of the CO_2 laser has not yet been revealed to the full, but experimental investigations have shed some light on its most important aspects. The overpopulation of the ν_3-level appears to result from a rather complicated process. At first, the oscillation level of the molecule N_2 is excited by direct electron blows during electric discharge. The probability of its excitation has a strong maximum at electron energies of 2 to 3 eV. The symmetric molecule N_2 cannot radiate oscillation energy

in the form of light. On collision with a CO_2 molecule it imparts energy to it, thereby exciting the ν_3-level. This process has a high probability because the excitation energy of the ν_3-level is very close to the energy of the lowest oscillatory level of N_2. If the laser does not contain N_2, the nitrogen is replaced by a CO molecule. The discharge results in many CO molecules because the energy of dissociation of CO_2 to CO and O is low (2.8 eV). But CO is less effective than N_2.

In a laser containing a mixture of CO_2 with N_2 the overpopulation of the ν_3-level is obtained not only through energy transfer from the nitrogen to the CO_2 in the lower oscillation state, but also through transitions from higher oscillation levels (quantum numbers 2 and higher) which are excited during the discharge.

The degree of overpopulation of the upper level in relation to the lower ones (ν_1 and ν_2) in a CO_2 laser increases also due to the rapid vacation of the ν_2- and ν_1-levels. The ν_2-level is vacated on collision between an excited CO_2 molecule and other molecules, especially N_2 and CO. The ν_1-level is vacated on collision with an unexcited CO_2 molecule. Here, either two molecules with the ν_2-level ($v=1$) are formed, or one with the ν_2'-level ($v=2$). As we know, upon collision the energy of the ν_2-level converts to the energy of translatory motion of molecules (thermal energy).

A small addition of water molecules greatly accelerates the vacation of the ν_1-level. The CO_2 molecule readily transmits the energy of the oscillation level ν_1 to the water molecule because water has oscillation states of closely similar energy. An admixture of helium increases the laser effect, probably because an electric discharge generates in helium electrons (helium is a monoatomic gas and it does need any

energy to excite oscillaton levels since it does not have them) which increase the total reserve of electrons suitable for exciting oscillation levels in the nitrogen. As a result of the combined effect of the above-listed factors, a powerful laser effect with a high efficiency is achieved.

It should be emphasized that the CO_2 molecule, like any other molecule, has rotation levels as well as oscillation ones. During discharges and thermal collisions this molecule receives rotation energy in quanta, but they are much smaller than oscillation quanta. In its rotation the molecule slightly weakens the bond between the atoms, and the oscillation level energy corresponding to the different rotation quantum numbers is different. Therefore, with different rotation quantum numbers a laser emits slightly different oscillation quanta, which differ in energy (although not very greatly, just by a few per cent) from those emitted with no rotation. The strongest laser effect in CO_2 is observed at rotation quantum numbers of 18 to 24. Having in mind the dependence of the laser effect not only on oscillation levels, but also on rotation ones, it is usually said that in the CO_2 device the laser effect is observed on oscillation-rotation levels of the molecule.

Due to their high output and efficiency CO_2 lasers are bound to find wide application.

Semiconductor Lasers

In 1964 a group of Soviet researchers under the guidance of the B.Wuhl, Corresponding Member of the USSR Academy of Sciences, was awarded the Lenin Prize for the development of semiconductor quantum light oscillators with an efficiency of

about 100%. The efficiency of gaseous and solid quantum generators, excited by a flash of light is below 1 per cent, while CO_2 lasers excited by an electric charge have an efficiency of around 10 per cent. Semiconductor quantum generators can be miniaturized. The early specimens made of a gallium arsenide crystal were 0.5 mm in size. The thickness of the oscillator active zone is of the order of a few microns, therefore the crystal for the oscillator may be still smaller than in the early specimens. Besides gallium arsenide, light generation can be achieved with the use of indium arsenide, indium phosphide, gallium arsenide-phosphide, and other compounds. One drawback of semiconductor lasers is the comparatively large width (spread) of the line of the light emitted. A gallium arsenide oscillator operating at the temperature of liquid hydrogen (—196°C) emits a wave of length 8430 Å with a line width of 0.1 Å. The line width relates to the wavelength approximately as $1:10^5$. In gas lasers this ratio reaches $1:10^{10}$ or even $1:10^{11}$. This ratio takes into account the line spread due to the inherent properties of the laser and also to weather changes and vibrations of the foundation on which it is installed. The frequencies (or the length of the emitted waves) of two identical lasers may differ by a factor of 10^{13}. Because of the relatively great line width semiconductor lasers are not used where a strictly constant frequency is required.

Semiconductors belong to the fourth group of the Periodic System of the Elements (silicon, germanium). Semiconductors made up of two or three chemical elements consist of compounds of elements belonging to the third and fifth groups (gallium arsenide, indium arsenide, gallium arsenide-phosphide), i.e. also to the fourth group "on the average". A semiconducting crystal contains excess electrons, which are

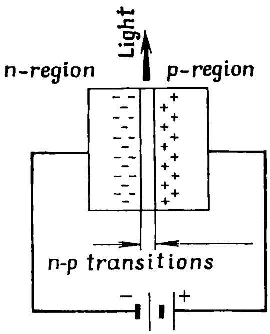


Fig. 33. Under the effect of an electric field electrons and holes accumulate at the boundary between crystals where *n-p* transitions occur. Light is emitted along the crystal interface.

very weakly bound with the crystal lattice. Under the action of external factors these electrons readily separate and give rise to electron conduction. Excess electrons appear when an element of the fifth group is admixed to a crystal from an element of the fourth group (germanium). Germanium atoms are bound with four electrons of an element of the fifth group, and the fifth electron is excessive and causes electron conduction. If an element of the third group is admixed to germanium, a single electron is not sufficient to fill the valency bonds of the germanium, and a "hole" with a positive charge appears in the crystal. Under the effect of an electric field an electron adjacent to the hole jumps over into the hole. A new hole forms at the site previously occupied by this electron; the hole is then filled by a new electron, and so on. The hole shifts along the crystal, giving rise to hole conduction. The electron states are called

n-states (negative) and the hole states, p-states (positive).

In complex crystals (gallium arsenide and others) electron and hole conductions are more intricate than those described above, but they also arise from admixtures of elements of the fifth and third groups, respectively.

In the semiconductor laser one half of the crystals, exhibit electron conduction and the other, hole conduction. If the negative pole of a d.c. source is connected to the n-side of a crystal (electron conduction) and the positive, to the p-side, the holes and electrons repulsed by the external source will accumulate at the interface. In this region electrons will begin to fill holes (these are so-called n-p junctions). But the energy of free electrons is higher than that of electrons residing in holes. The difference in energy is emitted in the form of light, the light propagates along the boundary between the crystals. If two opposite faces of a crystal which are perpendicular to the interface are polished, then part of the light, being reflected into the crystal, pushes the electrons into the holes, thereby causing induced radiation. The losses of electrons and holes are replenished by the external source of electric current. The electric energy is directly converted to light energy. This is the general principle of operation of the semiconductor laser.

Quantum amplifiers are bound to bring about revolutionary changes in various branches of science and technology. Quantum radio- and light-techniques hold great promise.

In conclusion we deem it our duty to name the precursors of Basov, Prokhorov and Townes in research on quantum amplifiers and oscillators. On June 18, 1951 an author's certificate was registered in the USSR for "A method for amplifying electromagnetic radia-

tions (ultraviolet, visible, infrared light and radio-waves)" based on the utilization of induced emission. The authors V.Fabrikant, M.Vudynsky and F.Butayeva proposed the idea of quantum amplifiers. True, the certificate did not cover the quantum oscillator. Recall that an oscillator has a resonator tuned to definite frequencies and emits radiation independently of the input signal. The amplifier increases the signal and it need not have a resonator tuned to the frequency amplified. Any oscillator can serve as an amplifier, but not the other way round. Most unfortunately the invention was not published until 1959, therefore Basov and Prokhorov, and Townes and his co-workers had to re-start the work from scratch.

Fabrikant was awarded the Vavilov Gold Medal for 1965 in recognition of his work on quantum optics.

Negative Absolute Temperatures

This subject is elucidated very comprehensively in a popular article by Professor D.Frank-Kamenetsky (*Priroda*, No. 3, 1960). We will only give you an idea of this unique phenomenon, which will be easy to understand because the preceding section supplies the necessary background.

We are used to the notion that temperature cannot go down below absolute zero and become negative. But actually this is not so, though the concept of negative temperature may seem a bit formal and is applicable only in rare cases. But it is quite a rigorous concept.

We know that an electron spin may have one of two orientations relative, for instance, to the orbital

momentum of the electron. The electron energy depends on spin orientation: it is higher with a parallel orientation and lower with an antiparallel one. The energy level of the electron splits in two and thus a fine level structure is formed. This should not be confused with the splitting of electron levels in an external magnetic field, i.e. the Zeeman effect, which is due to the different orientation of the total momentum (the orbital and spin momenta taken together) in a magnetic field. The total momentum can orient itself so that its projection onto the direction of the magnetic field changes by unity. Suppose the orbital momentum is equal to two. Then the total momentum splits in the absence of an external magnetic field into two fractions depending on the spin orientation: 3/2 (spin and orbital momentum are antiparallel) and 5/2 (they are parallel). This yields a fine structure. But then, in a magnetic field the level corresponding to the total momentum of 3/2 splits (Zeeman effect) into four states corresponding to the four projections of the total momentum onto the direction of the magnetic field: 3/2, 1/2, —1/2, —3/2, respectively. The splitting of the level with a total momentum of 5/2 yields six Zeeman lines corresponding to projections of 5/2, 3/2, 1/2, —1/2, —3/2, —5/2.

Now we will return to the energy levels determining the fine structure of the atomic spectrum. A fine structure is observed in the absence of an external magnetic field. The energy level of an atom may split, due to the interaction of the spin and orbital momenta, not only into two (a doublet) but into a greater number of levels. If a complex electron shell contains two electrons whose spins are parallel, the total spin is unity. It may take one of three positions relative to the orbital momentum: parallel, antiparallel and perpendicular; the total momentum will then change

by unity on each reorientation. The level will split into three sublevels (a triplet). Atoms containing more electrons may split into a greater number of levels, forming a more intricate fine structure.

Now we will revert to the two levels determined by the spin. When atoms collide in their thermal motion, they exchange energy, and a so-called thermal equilibrium is achieved between them. A thermal equilibrium is set up also between atoms residing on the lower and upper spin energy levels. At equilibrium, the number of particles in the upper energy state is smaller than that in the lower state, the ratio between the numbers of particles in the two states depends on the temperature and on the difference in the energy levels, it can be found by the following formula

$$n_2/n_1 = e^{-\frac{E_2 - E_1}{kT}} \tag{12}$$

Here n_2 and n_1 are the numbers of particles on the second and first levels, E_2 and E_1—the level energies, k—the Boltzmann constant, equal to 1.380×10^{-16} erg/deg, and T—the absolute temperature.

But the distribution of electrons (atoms) over the spin energy levels may depend not only on thermal collisions but on other factors as well; for instance, on the intensity of illumination of the atoms with light of the frequency needed to transfer electrons from the lower to the upper spin level ($\nu = \frac{E_2 - E_1}{h}$). This transfer can be effected also by an external alternating magnetic field, as is done in quantum paramagnetic amplifiers. Therefore the spin temperature may differ from that of the gas. At any rate, using the above expression, the notion of spin temperature

is introduced. Taking the logarithm of expression (12), one can write

$$T = -\frac{E_2 - E_1}{k \ln n_2/n_1} \tag{13}$$

Incidentally, this method is sometimes used to determine not only the spin temperature, but also the temperature of any system with two energy levels, E_1 and E_2. We will now dwell on the spin temperature.

Usually, there are fewer particles on the upper level than on the lower one, therefore the logarithm is negative and the temperature positive. The temperature reaches absolute zero when the logarithm tends to minus infinity, i.e. when all the electrons are on the lower spin level, and there are none on the upper level. This is absolute zero. If the population density of both levels is the same, the logarithm symbol is followed by unity. The logarithm of unity is equal to zero, and the absolute temperature reaches infinity. Imagine that the upper level is populated more densely than the lower one. Then the logarithm is followed by a value exceeding unity ($n_2/n_1 > 1$) and takes on a positive value, while the absolute temperature becomes negative according to expression (13).

A negative absolute temperature is higher than an infinite temperature in a certain sense. At first one must attain an infinite temperature, then raise it still higher, and it will finally become negative. At equilibrium, this is unfeasible, but we have seen that such states can be achieved in quantum amplifiers. These devices actually became possible only when scientists had learned how to obtain negative absolute temperatures.

By placing a substance in a magnetic field and splitting each of the spin levels into Zeeman ones

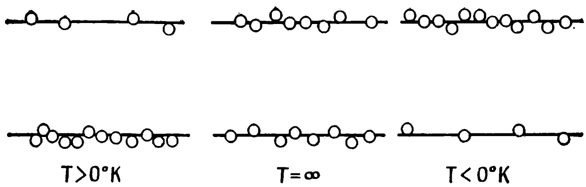


Fig. 34. Positive, infinite, and negative absolute temperatures. At a positive absolute temperature ($T > 0$°K) the upper level is less "populated" than the lower one. When both levels are "populated" equally, the absolute temperature is equal to infinity ($T = \infty$). If the upper level is "populated" less than the lower one, the absolute temperature is negative ($T < 0$°K). A negative temperature, as well as an infinite one, appears in non-equilibrium conditions when an external energy source causes overpopulation of the upper energy level.

it is possible to introduce the notion of temperature for Zeeman levels as it was introduced for levels characteristic of the fine structure. Here, a negative temperature is also possible; however, this will not be a spin temperature, but a negative Zeeman temperature if one may say so.

When considering the molecular quantum amplifier using ammonia we familiarized ourselves with the excitation of inversion oscillations of the nitrogen atom in the ammonia molecule. The separation of excited molecules has resulted in a negative temperature of inversion oscillations of the nitrogen atom. In all the cases considered there was a limited number of energy levels over which the particles were distributed. If there are many levels it is inconvenient to use the notion of non-equilibrium temperature because each pair of levels will have a temperature of its own. Therefore the concept of negative

absolute temperature is used for systems with a small number of energy levels.

We have spent enough time discussing the atomic electron shell and phenomena associated with processes occurring in it. We will now give some attention to the atomic nucleus and then revert to elementary particles.

Nuclear Synthesis Reactions

For recapitulation sake we will recall the meaning of the terms "binding energy" and mass defect. The nucleons in a nucleus are bound by very strong forces of attraction. Consequently, in order to separate nucleons to great distances one has to spend an energy equal to their binding energy in the nucleus. Nuclear forces greatly increase with reduction in the distance between the nucleons. Therefore, the closer the nucleons are to each other, the denser their packing, the greater is the work needed to move them apart. When nucleons join into nuclei, binding energy is released. The denser the packing of the final nucleus, the more energy is released. Binding energy escapes as radiation or the kinetic energy of nuclei transmitted to other particles after some time. Losing their energy, nuclei lose a mass equal to the energy divided by the square of the light velocity. Therefore the mass of the nucleus is less than the total mass of the nucleons comprising it. This magnitude is termed the mass defect. The mass defect indicates the energy which binds the nucleons in the nucleus. The higher the mass defect, the higher the binding energy. In nuclei with a small number of nucleons the mass defect is relatively small. When the number of particles increases, so does the mass defect. But if there are

very many nucleons, the nucleus will have many protons (it cannot contain neutrons alone), and the electric charge of the nucleus becomes very large. Electrostatic forces of repulsion between the protons increase, that is why the mass defect of excessively heavy nuclei decreases with increasing number of nucleons in the nucleus, thus it is maximal for medium-mass nuclei. Atoms in the middle of the Mendeleyev Table, approximately from silicon ($Z=14$) to tin ($Z=50$) have the greatest mass defect.

In light nuclei the mass defect increases unevenly as the number of nucleons in the nucleus grows. The first relatively stable nucleus among the light nuclei is helium-4. It contains two protons and two neutrons. The spins of protons, as well as those of the neutrons, are antiparallel in the helium nucleus, and the total nuclear spin is zero. Therefore there are no repulsion forces in the nucleus due to the spin- and spin-orbital forces mentioned above; the nucleus is packed in the best way for such a number of particles. The next maxima in the mass defect of light nuclei are observed in elements in which the number of particles is a multiple of that in helium-4. These are carbon-12 and oxygen-16. The spins of these nuclei are also zero. But there is no rigorous law here, because, as you will see below, nuclei are not built so primitively, they have their shells which are filled no less intricately than atomic electron shells. It should be noted that the structure of nuclei, especially heavy ones, is not quite understood yet. Their complexity stems from the fact that they contain two types of particles. Besides, the total number of particles in them is greater than the number of electrons in atoms.

If we take two light nuclei and join them together the packing of the final nucleus will be tighter and

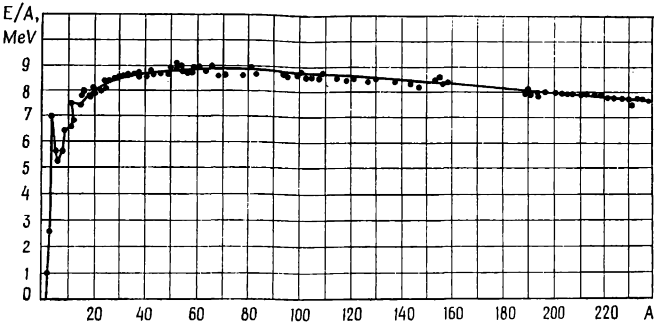


Fig. 35. The binding energy of a nucleon in a nucleus, or the mass defect per nucleon, is maximal for medium nuclei.

this will cause the release of a certain amount of energy. It is particularly advantageous if the ultimate product is a helium nucleus or a nucleus with a number of nucleons multiple of that of the helium nucleus. However, nuclei heavier than hydrogen isotopes are not suitable for synthesis reactions, as they have a high electric charge, and to bring two nuclei together one has to overcome the electrostatic force of repulsion, which is proportional to the product of the electric charges of the nuclei. The repulsion force can be overcome by imparting kinetic energy to the nuclei. To this end, the substance is heated and thus the relative velocity of motion of the nuclei increases. Even nuclei of deuterium and tritium, which have the lowest electric charge, have to be heated to very high temperatures up to tens or hundreds of kiloelectron-volts.

Hydrogen isotopes—deuterium and tritium—are the most suitable materials for nuclear synthesis. Because nuclei fuse together due to the high kinetic energy

obtained on heating, nuclear synthesis reactions are called thermonuclear reactions.

When two deutons join together, in 50 per cent of cases a nucleus of helium-3 and a neutron are formed. In this reaction 3.28 MeV of energy is released, of which 2.45 MeV is carried away by the neutron. In the remaining 50 per cent of cases the fusion of two deutons results in a proton and a tritium nucleus (triton). Here, 4 MeV of energy is released, of which about 3 MeV is carried away by the proton. When a triton fuses with a deuton a nucleus of helium-4 and a neutron are born. The reaction yields 17.6 MeV of energy, of which 14.1 MeV is accounted for by the neutron.

Reactions of fusion of deuterium with deuterium and of deuterium with tritium—more precisely, reactions between their nuclei—occur in a hydrogen bomb, whose explosive strength may equal that of tens, hundreds or millions of tons of TNT. The high temperature needed for a thermonuclear reaction is achieved in a hydrogen bomb with the aid of the explosion of a nuclear bomb based on nuclear fission.

There is an amazing pure quantum-mechanical effect, which enables one to carry out a thermonuclear reaction rather easily, it is the so-called tunnelling effect. To achieve the fusion of two deutons one has to bring them together, overcoming the electrostatic force of repulsion of like charges, to a distance within the range of nuclear forces of attraction (1.4 fermis). Taking into account that the deuton is slightly larger than the proton, the distance between the centres of two deutons should be about 3.5 fermis. To bring them together to such a distance upon head-on collision the "missile" deuton should be imparted a kinetic energy of about 1 MeV if the "target" deuton is at rest. If the two deutons are

moving towards each other with equal velocity, the kinetic energy is slightly lower, since in this case the collision products have neither an impulse nor a kinetic energy. Thus, the energy height of the so-called potential barrier set up by electrostatic forces of repulsion is about 1 MeV. From the standpoint of classical theory, reaction would take place exclusively between nuclei possessing a kinetic energy reserve of this order, and the deuterium would have to be heated to a temperature of about thousand million degrees to be able to penetrate the potential barrier. In reality a perceptible reaction occurs at a temperature a hundred times lower, when the kinetic energy of the incident deuton is about 10 KeV. At this temperature the deuton approaches the other deuton to a distance of about 200 fermis, where nuclear forces of attraction are equal to zero and the electrostatic force of repulsion is very strong. How does the synthesis reaction develop? To understand this we will have to recall the uncertainty relation. As the flying deuton approaches the target deuton its velocity decreases and so does the impulse, which is equal to the product of mass by velocity. At the shortest distance the impulse would seem to be equal to zero, i.e. have quite a definite value. This occurs when the deutons approach each other to a distance of 200 fermis. But according to the uncertainty relation the impulse and the coordinate of the particles cannot have precise values simultaneously. As the impulse approaches zero its uncertainty decreases, whereas the uncertainty in the particle coordinate increases. At a certain instant it may reach or even exceed 200 fermis. The incident deuton may, with equal probability, find itself at any point of a spherical volume of radius 200 fermis or more, it may also penetrate inside the target nucleus. Hence, due to

the uncertainty relation, there is a probability of synthesis reaction also at energies below the potential barrier. This probability increases sharply, exponentially, as they say, with a decrease in the difference between the barrier height, i.e. the energy necessary for surmounting the barrier (about 1 MeV in this case), and the relative kinetic energy of the particle. Reacting at energies below the one necessary for overcoming the potential barrier, the particle "passes through a tunnel" in it, i.e. pierces the barrier, though there is actually no hole or tunnel in it. This phenomenon is called the tunnelling effect, it is typical of the microworld. Classical physics, which describes the macroworld, knows no such phenomena.

Heavy nuclei emit alpha-particles in a similar way. In the usual (unexcited) state the kinetic energy of the nucleons inside the nuclei is lower than their binding energy. The potential binding energy depends on the position of the particle inside the nucleus, while the kinetic energy depends on the impulse. However, the position or the coordinate of the particle and its impulse cannot both have a definite value simultaneously, their uncertainties are related by equation (10). Because of this, just as in nuclear synthesis, there is a tunnelling effect for particles residing inside the nucleus. There is a probability that a particle will be emitted from the nucleus even when its kinetic energy is below its binding energy. The effect is observed in heavy nuclei because they are packed more loosely than light nuclei, their binding energy (barrier) is lower, and the kinetic energy of a particle inside the nucleus may be higher than in medium nuclei, since there are more particles in the nucleus. From time to time the kinetic energy concentrates in a small number of particles. Therefore the difference between the height of the poten-

tial barrier and the kinetic energy of the particles in heavy nuclei may be considerably lower than in medium and light nuclei. Here, the probability of the tunnelling effect increases. The particles would profit, energy-wise, by leaving the nucleus in densely packed groups—alpha-particles. Alpha-disintegration of nuclei, as well as emission, in certain cases, of protons, neutrons or deutons, differs in principle from emission of electrons or positrons, i.e. beta-radioactivity. In the first case particles already present in the nucleus escape from it. In the second case, electrons or positrons are born in the nucleus together with antineutrinos or neutrinos as a result of weak interactions, a process which is not fully understood yet.

It would be very important to realize a slow reaction of nuclear synthesis, the energy of which could be used for industrial purposes. Scientists of over twenty highly developed countries are working on this problem, but there are no practical results so far. It is very difficult to heat deuterium and tritium to the necessary temperatures of tens of kiloelectron-volts (hundreds of millions of degrees). It is still more difficult to confine the resulting plasma in an enclosed volume for the time necessary for the synthesis reaction. Nature has placed many traps and hurdles in the path to the solution of this extremely vital problem.

Science, however, has at its disposal unlimited resources, it will undoubtedly overcome all the difficulties, and mankind will have an inexhaustible source of power, a controllable thermonuclear synthesis reaction.

Liquid-Drop Nuclear Model and Fission Reactions

Heavy nuclei such as uranium are packed considerably looser than intermediate nuclei. Hence, if a heavy nucleus is divided into two medium fragments the nucleons will be packed more densely in each of them. A certain energy will then be released. Such a reaction is called a nuclear fission reaction. The feasibility of fission reactions became clear to the most far-sighted physicists immediately after the neutron was discovered.

In laboratory conditions, nuclear fission was first discovered by the German scientists O.Hahn and F.Strassmann in 1938. These scientists found in chemically pure uranium irradiated with neutrons barium ($Z=56$) and lanthanum ($Z=57$)—elements which are about half as heavy as uranium. The new elements could have appeared in the uranium only as a result of splitting of the latter under the action of neutrons. The way to Hahn and Strassmann's discovery had been paved by the investigations of Irène and Frederick Joliot Curie, who had discovered artificial radioactivity of elements in 1934 and then found lanthanum in neutron-irradiated uranium.

Uranium fission is accompanied by emission of two or three neutrons, which can fission two or three more nuclei. The number of released neutrons increases, under their effect the number of fissions increases, the process is progressively accelerated and an explosive fission chain reaction sets in. This reaction has been used in nuclear bombs.

Only uranium-235, uranium-233 and plutonium-239 (an artificial element) can fission under the effect of slow neutrons. Fission of uranium-238 requires a

higher neutron energy and the reaction has an energy threshold above 0.5 MeV. Among the fission neutrons very few have an energy higher then 0.5 MeV. Therefore uranium-238 serves as a kind of ballast, it is separated from the more valuable uranium-235. Natural uranium contains 0.714 per cent of uranium-235 and 99.28 per cent of uranium-238.

However, if uranium-238 is placed in a nuclear reactor together with uranium-235 it absorbs a slow neutron and upon emission of two electrons turns into plutonium-239, which is fissioned by slow neutrons and can be used in nuclear engineering.

On fission of a heavy (uranium or plutonium) nucleus about 200 MeV of energy is liberated of which around 165 MeV remains as kinetic energy of the fragments. Part of the energy is released on radioactive disintegration of the fragments which proceeds for a long time and has several successive stages. Fission of 1 kg of uranium releases an energy equal in explosive force to about 20 000 metric tons of TNT or to the combustion energy of 2000 tons of gasoline.

The range of nuclear forces is very small, therefore each nucleon interacts practically only with its nearest neighbours. This property of nuclear forces enabled Ya. Frenkel, Corresponding Member of the Academy of Sciences of the USSR, to represent the nucleus as a liquid drop in which particles also interact only with their nearest neighbours. The similarity between the nucleus and a liquid drop is prompted by the proportionality of the volume of the nucleus to the number of nucleons in it (the density of nuclear matter is nearly constant). It follows that nuclear forces are short-range forces: each nucleon interacts only with its closest neighbours. If it interacted strongly with far-off nucleons as well, an increase in the number of nucleons in the nucleus would

raise the binding energy, and nuclei of heavy elements would be denser than light nuclei. In 1939 Frenkel and, independently, Niels Bohr developed a theory of nuclear fission under the effect of neutrons which was based on the liquid-drop model. The neutron has no charge and therefore, on entering the nucleus without any hindrance, it loses its binding energy, equal to about 8 MeV, to the nucleus. Under the effect of the neutron energy the nucleus—a drop of electrically charged nuclear liquid—begins to pulse and splits into two approximately identical fragments.

In actuality the fragments are not equal in mass. On the average, one of them is about 95 nucleon masses (close to molybdenum-95) and the other, around 140 nucleon masses, these are the masses of a barium and a lanthanum isotope. The liquid-drop model does not yet enable one to explain the comparatively large asymmetry in the mass of fission fragments. This asymmetry, however, can be understood from the standpoint of the shell model, which will be described at a later stage.

In 1940 the then very young Leningrad scientists G.Flerov and K.Petrzhack discovered spontaneous fission of uranium, a very slow process: the half-life of uranium-238 is about 10^{16} years. Spontaneous disintegration of uranium-235 is ten times slower.

Later on spontaneous fission of many nuclei was discovered, it characterizes the instability of the nucleus and is of a statistical nature. This phenomenon proved to be associated with neutron-induced fission of nuclei. If we plot the cross section of fission induced by neutrons of different energy, the cross section of spontaneous fission will correspond to the zero energy point on the curve. The next point of the curve corresponds to the binding energy of the neutron in the nucleus (about 8 MeV).

The heavier the nucleus, the less stable it is. The nuclei of man-made elements fermium ($Z=100$) and mendelevium ($Z=101$) have very short lifetimes. The isotopes of these elements exist for just a few hours until spontaneous disintegration. The isotopes of elements with $Z=102$ and $Z=103$ (lawrencium) live still less.

Spontaneous fission, as well as neutron-induced fission, is in line with the liquid-drop nuclear model; the pulsing nucleus tears in two. Since no energy is introduced from without, the probability of this process is very low.

Nuclear fission reactions are easy to control. They can be made slow or fast. Control is effected by selecting the mass of the fissionable material and choosing its concentration, and also with the aid of rods absorbing neutrons in the reaction zone. The mass and concentration of the active material, as well as the dimensions of the nuclear reactor, are chosen beforehand and depend on the power output and purpose of the reactor. A reactor is provided with neutron absorbers. When introduced into the core (active zone) they stop the nuclear reaction completely. By partial withdrawal of the absorber from the core one can set definite operating conditions and power output.

Shell Model of Nucleus

Some facts do not seem to be in line with the liquid-drop structure of the nucleus. Nuclei with an even number of protons are more stable than nuclei with an odd number, and they occur in nature much more frequently than nuclei with an odd number of protons. An even number of neutrons in a nucleus also increases its stability. But the most stable nuc-

lei possessing the highest binding energy are nuclei with a number of protons or neutrons equal to 2, 8, 20, 50, 82. To these should be added nuclei with 126 neutrons and, according to some data, 138 and 146.

All these numbers are called "magic" numbers. The "magic" quality of nuclei is manifested, for example, in their "reluctance" to capture neutrons: their cross section of neutron capture which is accompanied by emission of gamma-quanta is extremely small. The alpha-particle energy of alpha-radioactive magic nuclei is also exceedingly small. The nuclei possess some other properties indicating their increased stability.

By analogy with electron levels it is assumed that the nucleus also possesses energy levels, or shells, filled to a greater or lesser extent with pairs of nucleons (two protons and two neutrons) whose spins are antiparallel. Nuclei with completely filled shells are the most stable, they acquire the "magic" quality.

We should emphasize one specific feature of heavy nuclei which we attribute to the shell structure. Why do heavy nuclei have a larger number of neutrons than medium and light nuclei? Due to the great number of protons in heavy nuclei, electrostatic forces of repulsion come into play. The distance between the protons increases, whereas the binding energy decreases. The nucleons "rise" to higher energy levels. Lower levels remain unfilled, protons cannot occupy them. They could be filled by neutrons because they have no electric charge and are not subjected to electrostatic forces of repulsion. It appears that in this case it is more advantageous energy-wise for a certain number of protons to turn into neutrons and occupy free low energy levels.

In nuclei having a certain "excess" of protons the latter turn into neutrons, emitting a positron and a

neutrino. This type of radioactivity was discovered by Irène and Frederick Joliot Curie.

Note that the proton is usually stable, its mass is below that of the neutron, and it cannot turn into a neutron outside the nucleus. It has no source to draw energy from. But inside the nucleus, when the proton is on a high energy level, it can obtain the energy necessary for transformation into a neutron by dropping to a lower energy level. Positron radiation is usually given off by man-made elements. Imagine a heavy nucleus into which we have injected protons or alpha-particles with the aid of an accelerator. The new, heavier nucleus will have an "excess" of protons, which will yield positron activity on disintegration.

The shell structure enables one to understand positron and beta-electron radioactivity and explains the fact that heavy nuclei have more neutrons than protons. The neutron is unstable outside the nucleus. As we have seen, it disintegrates into an antineutrino, emitting an electron. But once in the nucleus it becomes stable; for instance, in a deuton it lives for an indefinite period of time. In the nucleus, the neutron and the proton continuously transform into each other. This occurs with great frequency. After a lapse of about 10^{-24} sec the neutron turns into a proton. After the same period of time reverse transformation takes place. Naturally, the neutron, which has a comparatively large half-life, does not manage to disintegrate completely. The instant from which the lifetime of a neutron must be reckoned as related to spontaneous disintegration shifts all the time, and disintegration can never be completed. But conjure up a nucleus with a relatively large number of neutrons. By "relatively large" we mean more than the number of free levels with low energy. This may occur in two cases. First, it will happen if we place the

nucleus in a nuclear reactor and irradiate it with a dense neutron flux. If the nucleus does not fission under the effect of neutrons, it will absorb them and "fill to overflow". Second, a neutron excess results from fission of a heavy nucleus. Heavy nuclei contain a considerable excess of neutrons over the protons. On splitting, a heavy nucleus yields two medium fragments, which, when in the normal state, contain almost as many neutrons as protons. But the fragments, despite the fact that two or three neutrons were emitted by them during fission, contain more neutrons, their ratio to the protons corresponds to a heavier, not a medium, nucleus. In medium nuclei the nucleons "settle" in shells predominantly in pairs. The excess neutrons find themselves on higher energy levels, they isolate themselves from firmly bound pairs (more precisely "foursomes": two neutrons and two protons, occupying more advantageous energy levels). These excess neutrons do not interact with protons so frequently and turn into protons more rarely, exchanging charged pi-mesons. Their spontaneous disintegration and transformation into a proton becomes probable. Having turned into a proton, a neutron can occupy a lower energy level. Neutron disintegration and electron (beta-)radioactivity are advantageous energy-wise, because the neutron has an energy reserve for this: it is heavier than the proton, besides it occupies a higher energy level before disintegration.

The distribution of nuclei over the shells and their movement from one shell to another without perturbations becomes possible only due to the Pauli principle, which forbids more than one particle with a spin of 1/2 to occupy in a given state on each of the energy levels. Due to this principle particles settle over the levels in an orderly fashion, and if

all the lower levels are occupied and the nucleus is not excited, the shell structure of the nucleus is revealed. But it is not very stable since the nucleons are packed rather densely. Interacting, they easily push each other from their energy levels, and the shell structure collapses. It is destroyed if a high-energy particle, for instance a neutron, penetrates the nucleus. The levels are disturbed, the nucleons begin to move randomly, the excited nucleus resembles a liquid drop rather than a harmonious shell structure. But when a neutron penetrates the nucleus, some shells may remain intact. Then the pulsating drop will contain the remainder of the shell structure which gets into one of the fragments during fission. Such is the primitive explanation of the mass asymmetry of fission fragments, which were described in the preceding section.

There are several other nuclear models besides the liquid-drop and shell models. Their objective is to describe different properties of nuclei. The diverse nature of the atomic nucleus calls for more than one or two models. The shell model, however, enables one to describe the greatest number of experimental data from a unified standpoint. Its authors, M.Goeppert-Mayer (USA) and J.H.D.Jensen (FRG), have been awarded the Nobel Prize in physics for 1963. A rigorous theoretical substantiation of the shell model of the nucleus and its further development is due to the Soviet Academician A.B.Migdal.

Mössbauer Effect

A thirty-year-old German scientist R.Mössbauer developed in 1958 a so-called nuclear clock with a precision so high that if it worked a very long time

it would be just one second fast after one hundred thousand years' operation. The accuracy of the clockwork was about $1 : 10^{12}$. Mössbauer was awarded the Nobel Prize for this discovery in 1961.

Excited nuclei emit high-energy gamma-quanta (photons) associated with a high frequency. Photons simultaneously possess corpuscular and wave properties. Taking advantage of the wave properties of photons, their frequency or the corresponding cycle (time) of oscillations can be used as a time reference unit.

Nuclei emit photons (gamma-quanta) of different energy. Very energetic gamma-quanta emitted on transition of nucleons inside the nucleus from upper to lower energy levels are not suitable for this purpose. The reason will be explained below. The nucleus also emits softer gamma-quanta. The "liquid-drop" nucleus may oscillate, this being accompanied by deformation and pulsation. The oscillations are quantized. They are excited when the nucleus absorbs quite definite portions of energy—photons of strictly defined frequency. The nucleus shifts to a higher energy level. The oscillation energy may be emitted as a quantum, the nucleus emits a photon and drops to a lower oscillation energy level. Precisely these photons are used as a nuclear clock.

Leaving aside the practical end of the problem, let us imagine a source consisting of excited nuclei and emitting photons of a given energy (frequency). Place exactly identical, but unexcited nuclei at a certain distance from it. The photons emitted by the source and hitting the target will excite oscillations in the target nuclei—resonance oscillations. The target nuclei are excited under resonance and begin to emit photons. This happens when the frequency of the photons hitting the target precisely coincides

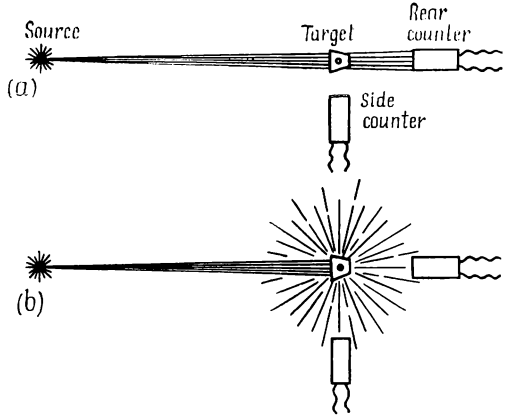


Fig. 36. The measurement set-up in the Mössbauer experiment. In the case *(a)* there is no resonance: the side counter does not show any readings, only the rear counter does. In the case *(b)* there is resonance: the side counter detects gamma-quanta emitted by the target due to appearance of resonance. The readings of the rear counter reduce as compared with those under no-resonance conditions.

with the frequency necessary to excite oscillations. Resonance absorption is revealed very easily. To this end use is made of two photon counters each of which consists of a crystal scintillator producing a light flash when a gamma-quantum penetrates it, and a photomultiplier, which transforms a weak light signal into a comparatively strong electric pulse. One counter is placed behind the target on the source-target line. This is the first scintillation counter. The second counter is also trained on the target, but it is placed at right angles to the first one. If there is no resonance, the frequency of the photons

emitted by the source does not coincide with the frequency of excitation of oscillations in the target nuclei, and the side counter does not show any readings. The rear counter records a certain gamma-activity emanating from the source. But when resonance arises and the target begins to absorb photons, the rear counter shows a reduction in the number of photons issuing from the target: part of them are absorbed by the target. But the target itself begins emitting photons. These photons are radiated uniformly in all directions, the side counter begins to show readings.

Thus, let us recapitulate: in the absence of resonance absorption the rear counter shows high readings corresponding to the photon flux unabsorbed by the target. The side counter is dead. When resonance absorption sets in, the rear counter indicates the weakening of the direct flux, while the side counter begins to count the photons issuing from the target and appearing on resonance absorption of direct photons.

Consequently, if the target emits photons, both nuclear clocks (source and target) show identical readings. The frequencies coincide. When the frequencies diverge, one of the "pendulums" swings faster, the resonance disappears, the target ceases to absorb and emit. This points to a different course of time at the locations of the emitter and the target.

The reader already realizes that with the use of nuclear clocks one can check different effects following from the theory of relativity developed by A. Einstein: such effects as, for instance, the slowing down of time on a moving object, which was predicted by the special theory of relativity, the acceleration of time on strengthening of the gravitational field and slowing down on weakening of the gravitational forces as predicted by the general theory of relativity.

We will not, however, dwell on the theory of relativity, it is described in many good books. We will only say that in our opinion the slowing down of time predicted by the special theory of relativity is not questioned by anybody, this effect has been thoroughly checked experimentally using the lifetime of mu-mesons, which is longer for flying mesons than for slowed-down ones. As for the general theory of relativity, experts assert that here quantitative measurements may prove very useful.

Now we will revert to the investigations of R.Mössbauer. So far we have just mentioned it in passing. The time measuring method, described above in general terms, or, more precisely, the method for comparing the speed of two nuclear clocks, was known long ago. But almost insurmountable obstacles had to be overcome before Mössbauer achieved his results.

In the first place, the energy of an emitted photon (as well as an absorbed one) is not quite the same, it exhibits some uncertainty: the spectral line of emission (and absorption) has a certain width which determines the precision of measurement of the photon frequency or the cycle of the associated oscillations.

According to the uncertainty principle the indeterminacy in the energy of the excited state of a nucleus depends on the time the nucleus remains in the excited state or, which is the same, on the lifetime of the nucleus as related to photon emission. The shorter the period during which the nucleus is in the excited state, the greater the uncertainty in the excitation energy, the greater the occasional changes in the energy and frequency of the emitted photon, and the poorer is the nuclear clock. Calculation shows that if gamma-quanta are emitted after a time during which the nucleus has been in the excited state comparable with the time characteristic of intranuclear

processes (10^{-23} sec), then at photon energies used in experiments the spread (uncertainty) in energy (and frequency) is so great that the precision of the clockwork is absolutely unsatisfactory. What use is a clock whose pendulum swings with an indefinite oscillation cycle? So, nuclear clocks require nuclei which remain in the excited state sufficiently long as compared with nuclear time. Such relatively long-lived excited nulcei, as well as those into which they transform after photon emission, are called isomeric nuclei. Nuclear isomery was discovered in 1936 by the Soviet Academician I. Kurchatov. The lifetime of excited isomeric nuclei until they drop to the unexcited state may reach a few years. The shortest time recorded so far—about 10^{-8} sec—is still many orders of magnitude longer than the characteristic nuclear time (10^{-23} sec).

The material considered to be most suitable for nuclear clocks is iron-57, which remains in the excited state for about 10^{-7} sec; the energy of the photon emitted by it is about 14 keV.

Dividing the quantum of action $\hbar$ by the lifetime of excited iron-57, we find the uncertainty in energy, which is equal to $1.05 \times 10^{-27}/10^{-7} \simeq 10^{-20}$ erg, or approximately 0.6×10^{-8} eV. This is the width of the level, the spread in the energy of the photons emitted and absorbed. But the photon energy itself is equal to 14 keV. Hence, the spread relates to the total energy approximately as $1 : 10^{12}$. But the energy is equal to the frequency multiplied by the quantum of action, $h\nu$, the frequency is proportional to the energy. Hence the frequency precision of the clock is equal to $1/10^{12}$.

Everything would seem to be right and precision well ensured. But we should take into account one more effect, which actually ruins the precision of

the clock. Now we are finally approaching the essential point. A photon flying out of a nucleus possesses an impulse, or momentum. On emission the total momentum of the nucleus-photon system should be conserved; it should be the same as for the nucleus before emission, i.e. zero. Therefore, in accordance with the law of conservation of momentum, at the instant of photon emission the nucleus receives the same impulse as the photon does, but in the opposite direction. Remember the recoil of a shotgun? According to the law of conservation of impulse the gun receives the same impulse (momentum) as the bullet, but acting in the opposite direction. The total impulse of the gun and bullet is zero, no matter how great the impulse was before the shot. The photon and nucleus pulses added together will also yield zero, as before emission. But the nucleus acquires a certain kinetic energy: the emission energy is shared between photon and nucleus. The kinetic energy of a particle is equal to the square of its impulse divided by the doubled mass. The lower the mass of a nucleus, the greater portion of energy it carries away on emission. The distribution of energy between nucleus and photon is inversely proportional to their masses. The photon mass can be found by dividing its energy by the square of the light velocity. The mass of the nucleus of iron-57 is known. By simple calculation we find that the mass of the nucleus is about 2×10^6 (two million) times as great as that of the photon. Thus, due to the recoil, which is similar to that of a shotgun, the nucleus carries away a radiation energy equal to $14\times10^3/2\times10^6=7\times10^{-3}$ eV. This is not so little, at any rate many times greater than the indeterminacy in the photon energy (the energy of the excited state of the nucleus), which is about 10^{-8} eV. Because of this loss the resonance is disturbed, in

this case the photon energy is insufficient to excite the nucleus of iron-57 in the target. But one must keep in mind that when a photon penetrates a target nucleus the latter also acquires, according to the law of conservation of impulse, an impulse equal to that of the photon. Together with the impulse, another 7×10^{-3} eV of translatory kinetic energy will be transmitted to the nucleus, and still less energy will remain to excite oscillations. Because of the recoil on photon emission and the increase in nuclear impulse on absorption of the photon by the target any hope to obtain resonance absorption seemed to vanish.

Incidentally, the indicated estimates have been supported by experiments in which a source placed on a centrifuge approached the target with the velocity necessary to offset the indicated energy losses. The resonance was restored at the calculated velocity. This confirmed the mechanism of energy leakage, but there was no practical advantage from such compensation by velocity. The clock could not be used. Besides, errors were introduced which were associated with the effects predicted by the theory of relativity. And it was precisely these effects that the scientists were going to study with the aid of nuclear clocks.

To eliminate the recoil, or at least to decrease its effect, the mass of the nucleus had to be increased to a maximum. The ingenious Mössbauer used a nucleus bound in the crystal lattice and in this way transmitted the recoil impulse not to a single nucleus, but to a whole system of many nuclei—the entire crystal. The mass of the system increased immeasurably, the energy transmitted to the nuclei decreased accordingly, the negative effect of the recoil of the nucleus was practically eliminated. In a target, nuclei are fixed in a similar way. It should be remem-

bered that if the photon energy is too high the nucleus may be knocked out of the crystal lattice by the force of the recoil, and the useful effect of the lattice will be reduced to zero. Therefore the photon energy cannot be very high.

Nuclei undergo thermal oscillation in the crystal lattice. Moving towards the target, they increase photon energy; moving away, they reduce it. In the same manner the energy and temperature oscillations of the target nuclei necessary for exciting the nucleus are changed. The temperature oscillations disturb the resonance. To do away with temperature oscillations, the crystal is cooled down with liquid nitrogen. At a very low temperature quantum effects become more pronounced. To excite some nuclear oscillations or other in the lattice, which are also quantized, an energy exceeding that of the corresponding quanta is required. But if the temperature is low (even if it is not absolute zero) no oscillations will be excited, because the available thermal energy is not sufficient to excite the oscillation level. Here we only speculate on the subject, but there are relevant calculations as well. At any rate, atoms of iron-57 are held firmly enough in the crystal, they are practically immobile at the liquid-nitrogen temperature, and photons emitted by the source are resonance-absorbed by a target which is at rest relative to the source.

But suppose the target is moving? If the relative velocity of the source and the target (it does not matter whether they are approaching each other or separating) is only 1 mm/s, the resonance in iron-57 disappears. On further increase in relative velocity to about 2 or 3 mm/s, however, the resonance reappears, but now it is slightly weaker than before. The appearance of several adjacent lines near the main line

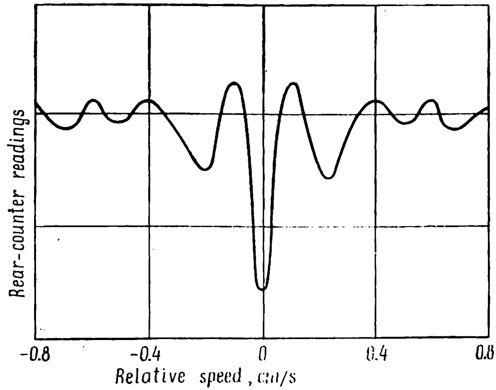


Fig. 37. Hyperfine splitting of energy levels of the nucleus. If the target is approaching the source (the difference, or relative velocity, is positive) or recedes from it (the relative velocity is negative), then, in addition to the main inverted peak of resonance absorption of gamma-quanta by the target (the deep valley at a zero speed on the curve showing the dependence of the rear-counter readings on the relative speed) additional absorption maxima appear as a result of hyperfine splitting of nuclear energy levels due to the different orientation of the nuclear magnets in the magnetic field of the crystal lattice.

is due to the hyperfine splitting of the energy level into several levels owing to the different orientation of the nuclear spins in the proper magnetic field of the crystal lattice. Projections of the nuclear spin may only have values differing by unity. Because of this the component of the magnetic moment along the direction of the external field (in this case, the magnetic field of the lattice) has discrete values. Therefore the energy of the principal oscillation level splits up, it becomes slightly higher when the component of the nuclear magnet is oriented so that its northern

pole looks in the same direction as does the northern pole of the lattice magnet. The energy is lower if they are oriented oppositely.

Incidentally, the hyperfine structure of oscillation resonance lines, which can be determined by investigating the appearance of side resonances as related to the relative velocity of the target and the source serves as a good method for determining magnetic moments of nuclei.

Resonance absorption is very sensitive to the relative velocity, it disappears at a relative velocity of about 1 mm/s. Such a high sensitivity of the method makes it possible to use it for studying the slowing down of time on objects moving relative to a fixed observer, which has been predicted by the special theory of relativity.

It now remains to tell you how the iron-57 isomer is obtained. Mind you, it exists only for about 10^{-7} sec. How can one handle it practically if it disintegrates so fast? In actual fact the source of gamma-quanta is usually a cobalt isotope, radioactive cobalt-57, which has a half-life of 270 days and transforms into an excited isomer of iron-57 after emission of an electron (and an antineutrino, of course). Thus, an iron isomer emitting the necessary gamma-quanta is obtained on the spot, directly in the set-up, as a result of disintegration of the cobalt. For the target, use is made of iron-57, it is contained in ordinary iron in the amount of 2.2 per cent.

A nuclear clock was used to check the conclusions following from the general theory of relativity right in the physical laboratory. According to the general theory of relativity the gravitational forces affect the course of time. Imagine a source of gamma-quanta—a nuclear clock—placed at the head of a flight of stairs. Photons arriving at the foot of the flight have a higher

frequency (blue shift) than those which are precisely in resonance with the target nuclei; their energy is higher than usual. The reason is that a photon, flying down from the top, becomes more energetic due to the force of gravity. It could not have accelerated, it had previously moved with a maximum possible velocity, the velocity of light. The gravitational field of the earth increases its energy, augments its mass. The increased energy is associated with a higher frequency, and an observer watching a nuclear clock on the ground floor gets an impression that his clock is slower than that installed on the upper floor, and he will insist that the other clock is fast. His clock cannot be slow, it is the most precise mechanism in the world, of course. But, though this is hard to admit, it is his clock that is slow: the time runs faster on the ground floor than indicated by his clock. The effect described is so negligible that in the example quoted the resonance does not disappear completely (the variation in frequency lies within the line width), but just weakens slightly.

The accuracy of the check-up of the conclusions stemming from the general theory of relativity is not very high as yet. In laboratory conditions, it has so far only been possible to establish qualitatively the existence of effects predicted by Einstein. More precise results may not be long in coming now.

Several dozens of other isomers exist besides iron-57. Many of them are suited for investigation of resonance absorption of gamma-quanta by nuclei. The Mössbauer effect has become a powerful tool in the studies of the properties of solids. By incorporating nuclei in different crystal lattices it is possible to determine, by the disappearance of the resonance, the energy at which nuclei are knocked out of the

lattice. This is how the binding force of the nucleus in the lattice is found.

Well, it is time now to revert to elementary particles.

Complete List of Elementary Particles

Ignoring the short-lived resonance particles, which disintegrate as a result of strong interactions and occupy a somewhat isolated position among the elementary particles, the total number of types of elementary particles (those detected experimentally and convincingly confirmed theoretically) is 35. These include antiparticles, which are also legitimate building blocks of the universe. Sixteen of them are known to us (see Table 2); each of them has its own duties. Some of them serve to build matter and antimatter, others are binding materials, and still others participate in some way or other in the transformation of one type of particle into another. We will dwell on them briefly.

Two particles out of the sixteen—the photon and the neutral pi-meson—are particles and antiparticles simultaneously. Besides, we have come across two neutrinos, the negative muon, the positive pion, and the proton and neutron. All these seven types of particles have their antiparticles: two antineutrinos, the positron, the positive muon, the negative pion, the antiproton, and the antineutron.

But in addition to the enumerated sixteen particles there are another nineteen:—the η-meson, two K-mesons (K^+ and K^0 and their antiparticles), and also seven hyperons (Λ^0, Σ^+, Σ^0, Σ^-, Ξ^-, Ξ^0, Ω^-) with

their seven antihyperons. The place of these particles in the structure of matter (and of antimatter) is not clear yet. The nucleons, together with the hyperons, form the family of baryons, heavy particles. The K-mesons and hyperons are called strange particles. This name came into being not only because the particles had appeared unexpectedly, come uninvited, in a manner of speaking. Strangeness has a precise physical definition and is characterized by a definite number. But we are not yet ready to speak about this.

Now have a look at Table 5 which lists all the 35 particles just mentioned.

Besides the mass in electron mass units, the Table indicates mass values in megaelectron-volts. They have been obtained by multiplying the rest mass of the particle by the square of the light velocity and converting the result to megaelectron-volts.

Each elementary particle is characterized by its mass, mean lifetime (if it is unstable), and electric charge. The charge of the known particles is equal to that of the electron, the positron, or to zero. It has been established that the neutron is neutral, on the average, but different portions of it are charged either positively or negatively. No elementary particles with a charge exceeding that of the electron (positive or negative) are known at present. However, resonance particles—baryons—with a charge equal to two positron charges have been discovered. They are described in the section on resonance particles.

An important particle characteristic is the spin, which is expressed in $\hbar$ units (the quantum of action h divided by 2π). We know of particles with a spin equal to 1/2, 0, and 1. Particles with a spin of 1/2—fermions—are great "individualists": no more than one fermion can reside in any one of the states. Par-

TABLE 5

ELEMENTARY PARTICLES*

Particle class	Particle symbol	Anti-particle symbol	Quantum nos: Isospin I, G-parity, Spin J, Parity P, $I^G(J^P)$	Mass, MeV	Mass, em	Mean lifetime, sec
Photon	γ	γ	$0,1(1^-)$	0	0	Stable
Leptons	ν_e	$\tilde{\nu}_e$	—	0	0	Stable
	ν_μ	$\tilde{\nu}_\mu$	—	0	0	ditto
	e^-	e^+	—	0.511006(2)	1	ditto
	μ^-	μ^+	—	105.659(2)	206.8	2.2×10^{-6}
Mesons	π^0	π^0	$1^-(0^-)$	134.975(15)	264.1	0.89×10^{-16}
	π^+	π^-	$1^-(0^-)$	139.574(14)	273.1	2.61×10^{-8}
	η	η	$0^+(0^-)$	548.6(4)	1073.6	10^{-18}-10^{-19}
	K^+	K^-	$1/2(0^-)$	493.82(11)	966.4	1.235×10^{-8}
	$\tilde{K}^0$	$\tilde{K}^0$	$1/2(0^-)$	497.87(16)	974.2	$0.87 \times 10^{-10} (K_1^0)$
						$5.68 \times 10^{-8} (K_2^0)$

Continued

Nucleons	p	$\tilde{p}$	$\frac{1}{2}\left(\frac{1}{2}^{+}\right)$	938.256(5)	1836.0	Stable
	n	$\tilde{n}$	$\frac{1}{2}\left(\frac{1}{2}^{+}\right)$	939.550(5)	1838.6	1.01×10^{-3}
Hyperons	Λ^0	$\tilde{\Lambda}^0$	$0\left(\frac{1}{2}^{+}\right)$	1115.58(10)	2183.1	2.51×10^{-10}
	Σ^+	$\tilde{\Sigma}^+$	$1\left(\frac{1}{2}^{+}\right)$	1189.47(8)	2327.7	0.81×10^{-10}
	Σ^0	$\tilde{\Sigma}^0$	$1\left(\frac{1}{2}^{+}\right)$	1192.56(11)	2333.8	$< 1.0 \times 10^{-14}$
	Σ^-	$\tilde{\Sigma}^-$	$1\left(\frac{1}{2}^{+}\right)$	1197.44(9)	2343.3	1.65×10^{-10}
	Ξ^0	$\tilde{\Xi}^0$	$\frac{1}{2}\left(\frac{1}{2}^{+}\right)$	1314.7(10)	2572.7	3.0×10^{-10}
	Ξ^-	$\tilde{\Xi}^-$	$\frac{1}{2}\left(\frac{1}{2}^{+}\right)$	1321.2(2)	2586.5	1.74×10^{-10}
	Ω^-	$\tilde{\Omega}^-$	$0\left(\frac{3}{2}^{+}\right)$	1674(3)	3276.9	1.5×10^{-10}

* See *Rev. Mod. Phys.*, **39.** No. 1, 1967.

ticles with a spin equal to 0 or 1 are called bosons. Any one of the states can be occupied by an arbitrary number of bosons.

The fourth column of Table 5 lists the values of the spin J, spatial parity P, isotopic spin I and (for non-strange bosons) the so-called G-parity. These quantum characteristics are represented in the combination I^G (J^P). For the π^0-meson, for instance, the symbol 1^- (0^-) means that $J=0$, $P=-1$, $I=1$, $G=-1$. Some information on the isotopic spin, strangeness and G-parity is given below.

Isotopic Spin

The nuclear forces between a proton and a neutron, a neutron and a neutron, and a proton and a proton arise as a result of operation of virtual mesons, sometimes charged, sometimes neutral. There is, besides, an electrostatic force of repulsion between protons, but now we are dealing with specific nuclear forces. Electrostatic and electromagnetic effects (which are relatively weak) only distort, though not very strongly, the action of nuclear forces. Taking this stand, one may forget about the great similarity between neutron and proton. That is why they have a common name, the nucleon. Moreover, as far back as the early thirties W. Heisenberg suggested that proton and neutron should be regarded as different states of one and the same particle. To distinguish them from each other Heisenberg introduced the quantum number—an isotopic spin equal to 1/2 for the nucleon. The isotopic spin may assume one of two values differing by unity: +1/2 and —1/2. When the isotopic spin is +1/2 a nucleon becomes a proton, and with —1/2, a neutron. In accordance with the two possible types of

the nucleon, a proton and a neutron form an isotopic doublet. The isotopic spin values of $+1/2$ and $-1/2$ are called zeta-projections, or zeta-components, of the isotopic spin.

It should be noted that the term "isotopic spin" is extremely unfitting, it makes one think of isotopes and rotation. In actual fact a neutron and a proton cannot be regarded as isotopes. Isotopes are elements with identical charges and different masses, while a neutron and a proton have different charges and almost identical masses. Neutrons and protons can by no means be called isotopes, they are rather isobars, i.e. elements having different charges but identical masses. Therefore some scientists tried to replace the term "isotopic spin" by "isobaric spin", but this new term did not stick. The term "spin" is also out of place because the difference between the neutron and the proton does not imply any rotation. The only justification here is the formal mathematical similarity. Mathematically, scientists treat the isotopic spin in the same way as the ordinary spin. In particular, projections of an ordinary spin onto the direction of the magnetic field are called zeta-components, they are quantized and take on integral values. In a similar manner, components of the isotopic spin are quantized and assume values differing by unity, though there is no zeta-direction in space here. The direction exists in a certain conventional isotopic space.

For the nucleon, an electric charge expressed in proton charges (the proton charge is equal to unity) is related with the projection of the isotopic spin by the following expression:

$$Q=1/2+I_z \tag{14}$$

Hence, if we substitute the values of I_z the proton

has a charge of 1, and the neutron, 0 (for the proton $I_z = 1/2$, for the neutron, $-1/2$).

A nucleon—an isotopic doublet—splits into two states: a proton and a neutron. But these states differ not only in electric charge. Owing to the difference in charge the nucleon should, in each of its states, interact somewhat differently with other particles and have different energies, and hence different masses in these states. Indeed, the masses of the proton and the neutron differ by about three electron masses, or by 0.16 per cent. This is natural because electromagnetic interactions are weaker by a factor of 2 to 3 than nuclear (meson, or strong) interaction.

The notion of the isotopic spin was conceived when analyzing nuclear forces, their charge independence. Naturally, it is applicable exclusively to particles participating in strong interactions. With regard to the leptons and the photon this notion has no meaning. Of the familiar particles, strong interactions involve pi-mesons, they "bond" nucleons together. Pi-mesons form an isotopic triplet. One can guess right away that the isotopic spin of the pion is equal to unity. Only unity can produce three projections differing by unity: $+1$, 0, and -1. These three values of the zeta-component of the isotopic spin are associated with the positive, neutral and negative pi-mesons. For pi-mesons, the charge is equal to the zeta-component of the isotopic spin. As would be expected, the mass of the neutral pi-mesons differs from that of the charged ones. This difference (about 9 em) is about 3.3 per cent, it is also due to the difference in charge.

Before passing over to the new particles we should recall the antineutron and antiproton. This pair also forms an isotopic doublet. Its isotopic spin is equal to 1/2, the component $-1/2$ labels the antiproton,

and $+1/2$, the antineutron. For antinucleons the charge is equal to

$$Q=-1/2+I_z \tag{15}$$

There is a so-called baryon number B, which is equal to $+1$ for the nucleon, -1 for the antinucleon, and 0 for the pi-meson. With the use of the baryon number and the zeta-component of the isotopic spin the particle charge is defined as

$$Q=1/2B+I_z \tag{16}$$

It is significant that the pi-meson isotopic triplet contains both particles and antiparticles. At the same time the nucleons and antinucleons are separated into different doublets, although their mass is the same. Why so? The point is that four particles (two nucleons and two antinucleons) cannot be combined into a single quadruplet. Its isotopic spin would then be equal to 3/2, and the zeta-components for the neutron and antineutron would have opposite signs, $+1/2$ and $-1/2$. But the neutron and antineutron have no charges, they are both neutral and cannot be assigned different signs of the zeta-components in a single multiplet. The existence of a neutral particle and its companion neutral antiparticle calls for division of particles and antiparticles into different multiplets. The pi-mesons are the happy exception. The neutral pi-meson is simultaneously a particle and an antiparticle. This circumstance allows combining all the pi-mesons in a single isotopic triplet. The eta-meson coincides with its antiparticle and has no electric charge. Its isospin is equal to zero, it is an isotopic singlet.

Table 6 gives the values of the isotopic spin for mesons and baryons.

The K-mesons as well as the nucleons, have to be

TABLE 6

ISOTOPIC SPIN, ZETA-COMPONENT OF ISOTOPIC SPIN, AND STRANGENESS FOR MESONS AND BARYONS

Particles	Isotopic spin	Zeta-component of isotopic spin	Strangeness
π^+, π^0, π^-	1	1, 0, —1	0
η	0	0	0
K^+, K^0	1/2	1/2, —1/2	+1
$K^-, \tilde{K}^0$	1/2	—1/2, 1/2	—1
p, n	1/2	1/2, —1/2	0
$\tilde{p}, \tilde{n}$	1/2	—1/2, 1/2	0
Λ^0	0	0	—1
$\tilde{\Lambda}^0$	0	0	+1
$\Sigma^+, \Sigma^0, \Sigma^-$	1	1, 0, —1	—1
$\tilde{\Sigma}^+, \tilde{\Sigma}^0, \tilde{\Sigma}^-$	1	—1, 0, 1	+1
Ξ^-, Ξ^0	1/2	—1/2, 1/2	—2
$\tilde{\Xi}^-, \tilde{\Xi}^0$	1/2	1/2, —1/2	+2
Ω^-	0	0	—3
$\tilde{\Omega}^-$	0	0	+3

divided into two doublets. The neutral lambda-hyperon has an antiparticle. Therefore two neutral particles of identical mass cannot be combined into a doublet. Each of them forms an isotopic singlet with a zero isotopic spin. Sigma-hyperons, as well as anti-sigma-hyperons, form isotopic triplets, xi-hyperons (and antixi-hyperons) forming doublets. The omega-minus-hyperon, like the antiomega-minus-hyperon (a positively charged particle), forms isotopic singlets. Their isotopic spins are equal to zero. Classifying hyperons by their isotopic spin helped to discover neutral sigma- and xi-hyperons. At first, only charged sigma-hyperons were known. Due to their electric charge they leave tracks on thick photographic emulsions, therefore they could be recorded. But scientists

failed to obtain an isotopic doublet from a positive and a negative sigma-hyperon. Some investigators suggested that the sigma-hyperons should be assigned a unit isotopic spin. Then the component +1 would yield a positive sigma-hyperon, and the component —1, a negative one. Besides, there had to be a neutral sigma-hyperon corresponding to a zero zeta-component. Scientists began to look for it and finally found it after extremely thorough investigations. By similar reasoning they found the neutral xi-hyperon as well.

Each isotopic multiplet has a charge centre. Thus, the charge centre of the pi-meson multiplet is equal to zero. It can be found by summing up all the charges (in this case their sum is equal to zero) and dividing the result by the number of particles. For the nucleon multiplet the charge centre is equal to 1/2, for the antinucleon one, —1/2. A knowledge of the position of the charge centre of the multiplet will come handy in the next section.

In conclusion it should be noted that strong interactions obey the law of conservation of isotopic spin. So far, not a single case of violation of this law has been detected. In strong interactions the zeta-component of the isotopic spin is naturally retained, because it determines, together with the baryon number (which is also retained), the charge, which is always preserved. In weak and electromagnetic interactions the law of conservation of the isotopic spin does not hold good. The isotopic spin has nothing to do with these interactions. Weak interactions no longer "pay heed" to the more fundamental laws, such as the conservation of spatial parity; one cannot expect them to obey laws which do not refer to them.

Strangeness

The middle charge of the isotopic pi-meson triplet (its charge centre) is equal to zero. The middle charge of the K-meson doublet is equal to $+1/2$. The charge centre of the K-meson doublet is displaced by $+1/2$ relative to the centre of the pi-meson multiplet. This value, after being doubled, is called strangeness, or the strange number. The strangeness of K-mesons is thus equal to $S=+1$ (see Table 6).

A similar method can serve to determine the strangeness of the other strange particles. But the other strange particles — hyperons — refer to the baryon group. Therefore the displacement of the charge centre of each hyperon multiplet is determined with reference to the charge centre of a related, but not a strange, group of particles, with respect to the nucleon doublet. The middle charge of the nucleon doublet (its charge centre) is equal to $+1/2$. The lambda-zero-particle is neutral, it forms a multiplet all alone, i.e. it is an isotopic singlet. Its charge is displaced by $-1/2$ relative to the middle charge of the nucleon. The strangeness of the lambda-zero-particle is thus equal to -1. The charge centre of the isotopic triplet of sigma-hyperons is equal to zero. Therefore the strangeness of sigma-hyperons, as well as that of the lambda-hyperon, is equal to -1. The middle charge of a doublet of xi-hyperons is $-1/2$, it is displaced by -1 relative to the charge centre of the nucleon, the doubled value of the displacement (strangeness of xi-hyperons) is -2. The charge of the omega-minus-hyperon (or the charge of the omega-minus-singlet, which is the same) is equal to -1, while the middle charge of the nucleon multiplet is $+1/2$. Consequently, the charge of the omega-minus-hyperon is displaced by $-3/2$ relative to the middle charge

of the nucleon, while the doubled value, i.e. the strangeness, of the omega-minus-hyperon is equal to —3. The strangenesses of antihyperons are determined in a similar way, they are presented in Table 6 together with the strangenesses of hyperons. The strangeness of the antihyperon is equal to that of the hyperon, but with the opposite sign.

Now we can generalize the relation connecting the zeta-component of the isotopic spin and the baryon number with the charge, Q, of the particle. To the right-hand side of equation (9) we must add the displacement of the charge centre, i.e. half of the strange number,

$$Q=1/2B+I_z+1/2S \qquad (17)$$

If the strangeness is equal to zero (in pi-mesons and nucleons), equation (17) turns into relation (16).

The strange number was introduced by M.Gell-Mann (USA, 1953) and K.Nishijima (Japan, 1955). Strange particles form on collision of high-energy protons with other protons or of fast pi-mesons with protons.

Scientists could not understand for a long time why strange particles are never born single. If it is a hyperon, it is always born together with a K-meson or even with two K-mesons. The introduction of the strange number and establishing the fact that strangeness is retained in strong interactions helped to crack this puzzle. Suppose, for instance, two high-energy protons collide. Their total, as well as individual, strangeness is equal to zero. Consequently, the strangeness of the reaction products should also be equal to zero. But if the collision results in a xi-hyperon with a strangeness of —2, the strangeness can be retained only if two K-mesons are also born, each with a strangeness of +1. Besides the law of conser-

vation of strangeness, the law of conservation of baryon number should also hold good. Therefore, in the indicated reaction two other baryons are born in place of the two protons; one of these baryons is a proton and the other, a xi-hyperon. It is easy to see that the charge is also retained in this case. One more way of retaining the strangeness is possible: the birth of a xi-hyperon together with an antixi-hyperon of strangeness $+2$. But according to the law of conservation of baryon number both protons should remain, because the baryon number of the xi- and antixi-particles taken together is equal to zero. This reaction, however, requires a higher energy than the birth of a xi-hyperon together with two K-mesons. Therefore, when the energy of the colliding protons is insufficient, the birth of a xi-particle together with an antixi-particle is impossible.

A collision of a negative pi-meson with a proton may produce (in such cases the law of conservation of strangeness operates) a lambda-zero and a K^0, a sigma-minus and a K^+, while a sigma-plus and a K^- cannot be born. In the first two cases the total strangeness after the reaction is equal to zero, as in the initial particles. In the third case the K^- refers to an anti-K-meson doublet with a strangeness of -1. The total strangeness of a sigma-plus and a K^- is -2, and not zero as would be expected. The law of conservation of strangeness does not hold. In strong interactions it explains many prohibitions in the birth of strange particles; this law enables all allowed reactions to be written down.

The law of conservation of strangeness forbids strange particles to disintegrate rapidly as a result of strong interactions. Thus, for instance, according to the law a lambda-zero or any sigma-hyperon with a strangeness of -1 would have to disintegrate into

a K and a xi, which is impossible energy-wise: the total mass of a K and a xi is much greater than that of a lambda- or a sigma-hyperon. Strong disintegrations are excluded for these particles. The only possibility is disintegration as a result of weak interactions which are not covered by the law of conservation of strangeness.

Incidentally, the law of conservation of the strange number in reactions is not an independent law, it follows from other, familiar laws. Equation (17) can be resolved with respect to strangeness and written down as

$$S=2(Q-I_z)-B \tag{18}$$

In strong interactions the zeta-component of the isotopic spin is retained. The charge and the baryon number are retained in all reactions. This means that if a particle with a positive charge is born in the reaction, a particle with a negative charge should be born as well. If the positive charge disappears, so does the negative charge. A typical example of reactions with charge conservation are the birth and annihillation of pairs. Positive or negative charges are not accumulated in the universe. The same goes for the conservation of the baryon number. If a baryon is born, an antibaryon must appear too. Their baryon numbers are equal to unity, but opposite in sign; on birth of a pair (baryon and antibaryon) the baryon number increases by unity and simultaneously decreases by unity, i.e. actually remains unchanged.

Equation (18) shows that the law of conservation of strangeness follows from the laws of conservation of charge and of baryon number, which operate in any interactions, and also from the law of conservation of isotopic spin component, which holds good only in strong interactions. Since the isotopic spin

component is not retained in weak interactions, the law of conservation of strangeness ceases to operate as well. Strange particles disintegrate, like ordinary ones, as a result of weak interactions. But this is already slow disintegration, the lifetime of K-mesons and hyperons (see Table 5) is of the order of 10^{-10} sec. It is one million million times as long as the time of disintegration resulting from strong interactions.

G-Parity

This quantum characteristic (quantum number) refers only to mesons because they are bosons, they have an integral spin, and they are not strange bosons (their strangeness is equal to zero).

The physical meaning of G-parity is not easy to explain to a layman. It may assume values of $+1$ and -1 and is calculated by the formula

$$G=(-1)^{l+I}$$

where l is the angular momentum. For a single particle it is a spin, for two particles (G-parity has a meaning also for two particles, for instance, for the pair K and $\widetilde{K}$, whose strangeness totals up to zero) it is an orbital angular momentum.

As can be seen from the equation, G-parity is a product of two values

$$G=(-1)^{l}\ (-1)^{I}$$

The first is the quantum number of charge conjugation as calculated for the neutral component of the isotopic multiplet.

The mesons listed in Table 5, as well as the meson resonances of Table 6, are divided into two types

as regards the value of $C=(-1)^l$: even- and odd-numbered types according to their charge conjugation, and hence they have different symbols.

Mesons even-numbered according to charge conjugation, $C=(-1)^l=+1$:

Symbol	η	π	K	$\widetilde{K}$	η'
$I^G(J^P)$	$0^+(0^-)$	$1^+(0^-)$	$1/2(0^-)$	$1/2(0^-)$	$0^+(2^+)$

Mesons odd-numbered according to charge conjugation, $C=(-1)^l=-1$:

Symbol	φ	ρ	K^*	$\widetilde{K}^*$	φ'^*
$I^G(J^P)$	$0^-(1^-)$	$1^+(1^-)$	$1/2(1^-)$	$1/2(1^-)$	$0^-(1^-)$

Since the spins in the mesons in the upper line ($\eta,\pi,K,\widetilde{K},\eta'$) is even-numbered, the value of $C=(-1)^l=$ $=+1$ is positive. For the odd-numbered spin (the lower line) the value of $C=(-1)^l=-1$ is odd.

To calculate the G-parity, one should use the value of the isotopic spin. For a pi-meson, for example, $I=1$. Using the above formula, we find the G-parity for the pi-meson

$$G=(-1)^{l+I}=(-1)^{0+1}=-1$$

Now we will say a few words about symbols. Mesons and mesic resonances having a zero hypercharge and a zero isotopic spin were formerly denoted by η. But these particles may have different G-parity depending on the ordinary spin if their isotopic spin is the same. At present such mesons and resonances with a positive G-parity are denoted by η, and those with a negative parity, by φ. Mesons (resonances) with a zero hypercharge and an isospin of $I=1$ were formerly

* If two resonances have the same quantum number one is distinguished from the other by a prime superscript.

designated by π. Today the symbol π denotes only those of them which have $G=-1$, while mesons with an isospin equal to unity and a positive G-parity are designated by ρ. Thus, the following symbols are used now

$$Y=0\left|\begin{array}{llll} I=0, & \eta \text{ for } G=+1, & \varphi \text{ for } G=-1 \\ I=1, & \rho \text{ for } G=+1, & \pi \text{ for } G=-1 \end{array}\right.$$

K-mesons have no G-parity, but a K-$\widetilde{K}$ pair, for instance with parallel isospins $I+I=1$ and a unit orbital momentum, has a G-parity equal to $G=(-1)^{1+1}=+1$. The same pair, but having no orbital momentum, has a G-parity equal to $G=(-1)^{1+0}=-1$. In strong interactions, for instance in strong disintegrations of resonances, the G-parity is retained. The other quantum characteristics, such as strangeness and angular momentum, are also retained, of course.

K-Mesons

A positively charged K-meson was first discovered by the Bristol research group (Great Britain) in 1949. The group found in cosmic rays a particle disintegrating into three charged pi-mesons:

$$\tau \longrightarrow \pi^+ + \pi^+ + \pi^- + 75 \quad \text{MeV}$$

The particle was named the positive tau-meson.

In 1954 scientists discovered a particle which was also positively charged and disintegrated into a mu-meson and a neutrino, and in 1956 a charged particle was found which disintegrated into two pi-mesons (π^+ and π^0). It received the name of the theta-particle (θ). Besides the above schemes of disintegration into two and three particles, researchers discovered other paths of disintegration of tau- and theta-particles.

Disintegration into two particles in one case and three in another contradicted the law of conservation of parity, which had been considered unshakable until 1957. But it was precisely the different ways of disintegration of tau- and theta-particles (which were otherwise completely identical) that suggested to Lee Tsung-Dao and Yang Chen-Ning the possibility of non-conservation of parity in weak interactions; this idea was soon brilliantly confirmed by experiment. After that tau- and theta-particles were firmly considered one and the same *K*-meson.

As far back as 1947 G.Rochester and C.Butler of Manchester had found, also in cosmic rays, a previously unknown neutral particle which disintegrated into two charged particles leaving a track in the shape of the letter V (two diverging rays). The particle was named the *V*-particle, and various research groups began to collect examples of disintegration of the *V*-particle. In 1951 a group including Butler showed that there are at least two different neutral *V*-particles. One of them is a neutral hyperon (lambda-zero) disintegrating into a proton and a negative pi-meson. Identification of the second particle took another two years of strenuous work. In 1953 scientists found a neutral theta-particle disintegrating according to the scheme

$$\theta^0 \rightarrow \pi^+ + \pi^- + 214 \text{ MeV}$$

This, incidentally, was the very particle which Rochester and Butler had observed in 1947. Later on, disintegration of a theta-zero particle into two neutral pi-mesons was observed. Still later physicists discovered disintegration of a neutral *V*-particle into three pi-mesons (π^+, π^- and π^0, or π^0, π^0, π^0); the corresponding particle was named the tau-zero-meson.

It was clear that the neutral theta- (as well as tau-)

meson belongs to the K-meson group. But classification of the K-particles was possible only with the aid of the above scheme of distribution over isotopic multiplets. The result proved to be extremely interesting and probably understandable only to theoreticians, since they are aided by mathematical analogies. We will only mention that there is (as explained in the section on the isotopic spin) a neutral K-meson and its antiparticle, the anti-K-zero-meson. But both represent, roughly speaking, a mixture, or superposition, of two mesons: K_1^0 (theta-zero), and K_2^0 (tau-zero) taken in different proportions. The wave function describing the K^0- and anti-K^0 represents a superposition of functions referring to the K_1^0 and K_2^0. The K_1^0 (theta-zero) disintegrates almost exclusively into two particles, while the K_2^0 (tau-zero), into three. A great achievement of theory is the prediction of different lifetimes for the K_1^0- and K_2^0-mesons. As can be seen from Table 5, the second particle, or state, lives about 600 times longer than the first.

From the foregoing it can be seen that if we take a beam of K^0- (or anti-K^0-)mesons, part of it will disintegrate rapidly; within about 10^{-10} sec the beam will be free of K_1^0, while the remaining part of the beam will live on for some time (6×10^{-8} sec) until the K_2^0 disintegrate. The same is true of the anti-K^0-meson.

We are now facing a rather vague situation: there are two concepts: on the one hand, neutral K-mesons are supposed to split into a particle and antiparticle, and, on the other, they are subdivided into two mesons, K_1^0 and K_2^0, which have no antiparticles and have different lifetimes. How can we reconcile these two very distinct notions? The point is that neutral

K-mesons behave differently in different interactions. In strong interactions, when they are born or when, colliding with nucleons (or hyperons), give birth to other particles, the subdivision into K^0 and anti-K^0 holds good (it stems from classification by isotopic spins). This classification refers to strong interactions and has no meaning for weak ones. But when a particle exists without interacting with other particles and disintegrates spontaneously under the effect of internal (weak) interactions, the properties associated with these interactions come to the fore, the isotopic spin has nothing to do with it, the particles behave as K_1^0 and K_2^0. When dealing with the microworld one should be prepared for all kinds of surprises, of which the most frequent are the seemingly incompatible properties of particles. But on detailed analysis one finds that each of these properties is a manifestation of the diversity of nature, it is revealed in a definite specific situation. In different conditions, other properties are most prominent. Neutral K-mesons are one of the examples.

Charged K-mesons are obtained in accelerators by "shooting" protons at a target made, for instance, of copper or tantalum. As a result K-mesons are born among other particles. The number of positive K-mesons is usually from 1 to 5 per cent as related to the positive mu-mesons. Positive K-mesons appear most readily together with lambda-zero-hyperons. This reaction has a relatively low energy threshold (1.57 GeV) and satisfies the law of conservation of strangeness: the strangeness of the K^+-meson is $+1$, that of the lambda-zero, -1, and the sum is equal to zero, as with the proton and the target.

The negative K-meson has a strangeness of -1, it can be born only together with a K^+; the threshold

of this reaction is 2.5 GeV, therefore negative K-mesons are obtained in a much smaller number than positive ones (only about 0.01 per cent).

The lifetime of negative K-mesons can be determined only from their disintegration in flight. They, like negative mu- and pi-mesons, are captured by atoms, rotate in orbits around nuclei like electrons, but at radii as many times smaller as the mass of the K-meson is greater than that of the electron. Approaching the nucleus, a K^--meson is captured by it before its natural lifetime expires.

According to the laws of conservation of strangeness, of charge, number of baryons, and energy, the capture of a K^--meson by a proton leads to a series of extremely interesting reactions. The proton, having absorbed a K^-, which has a strangeness of —1, turns into particles with the same strangeness:

$$K^- + p \rightarrow \left| \begin{array}{l} \Sigma^+ + \pi^- + 103 \text{ MeV} \\ \Sigma^0 + \pi^0 \\ \Sigma^- + \pi^+ + 95 \text{ MeV} \\ \Lambda^0 + \pi^0 + 182 \text{ MeV} \\ \Lambda^0 + \pi^+ + \pi^- + 38 \text{ MeV} \\ \Lambda^0 + \pi^0 + \pi^0 + 34 \text{ MeV} \end{array} \right.$$

Sigma- and lambda-zero-hyperons can also arise from the capture of a K^0-meson by a neutron and absorption of a K-particle by a deuton.

In conclusion it is appropriate to recall that all K- as well as pi-mesons are spinless; more precisely, their spin is equal to zero. Therefore they do not obey the Pauli principle, and any at all number of K-mesons can be in the same state. They cannot, however, be considered heavy pi-mesons as mu-mesons are considered heavy electrons. In nuclear interactions the

isotopic properties of the nuclear particles are extremely important. The isotopic spin of K-mesons, however, differs from that of pi-mesons. For the former it is equal to 1/2, for the latter, —1.

Hyperons

We have spoken enough about hyperons. Their properties can be seen from Tables 5 and 6. All hyperons have been observed experimentally. The existence of antihyperons is confirmed by the charge-conjugation principle. According to this principle each particle must have its antiparticle. One of the antihyperons —the antisigma-minus-hyperon—has been found experimentally in Dubna, USSR (Joint Institute for Nuclear Research) by a group of physicists under the guidance of the Soviet Academician V.Veksler and the Chinese scientist K.C.Wang as a result of scanning about 40 thousand photographs.

In March 1962 a large group of scientists from the USA, Switzerland and France published an experimental proof of the existence of the antixi-minus-hyperon. This positively charged particle is born together with a minus-xi-hyperon on bombardment of protons with a beam of high-energy (3.3 GeV) antiprotons. The antixi-minus-hyperon disintegrates into a positive pi-meson and an antilambda-hyperon. The latter turns into an antiproton and a positive pi-meson.

In February 1964 a paper was published in which 33 authors, most of them workers of the Brookhaven Laboratory (led by R.Shute and N.Sermios), proved the existence of the omega-minus-hyperon. This particle has a mass of 1686 ± 12 MeV (about 3400 em), a strangeness of $S = -3$, and a lifetime of about 10^{-10} sec. The existence of the particle, its mass and stran-

geness had been predicted on the basis of a theory developed by M.Gell-Mann (USA) and Y.Ne'eman (Israel). According to the same prediction, the spin of the omega-minus-hyperon is equal to 3/2, and its isotopic spin, to zero.

As a result of an analysis of 100,000 photographs obtained in a 2-m hydrogen bubble chamber one case of birth of an omega-minus-hyperon was found in a reaction

$$K^-+p=\Omega^-+K^++K^0$$

It is easy to see that this reaction satisfies the law of conservation of strangeness.

The omega-minus-hyperon cannot disintegrate as a result of a strong interaction, like resonances do (see p. 231). In any disintegration the laws of conservation of baryon and electric charges hold good, and in strong interaction the law of conservation of strangeness is obeyed as well. Therefore the omega-minus-hyperon would be expected to disintegrate "in the strong way" into a K^-, an anti-K^0-meson and a lambda-hyperon. All the above-enumerated laws would be fulfilled. The total mass of the two K-mesons and the lambda-hyperon, however, is approximately equal to 2100 MeV, which is much higher than the mass of the omega-minus-hyperon. Disintegration with an increase in mass is forbidden energy-wise. Disintegration into other particles with a total strangeness of $S=-3$ and a baryon charge $B=1$ is forbidden still more rigorously. Therefore the omega-minus-hyperon is resistant to strong disintegrations and splits only as a result of a weak interaction, which is not covered by the law of conservation of strangeness.

All hyperons, except Ω^{-1}, have a spin of 1/2. It has been proved experimentally that the spin of the lambda- and sigma-hyperons is equal to 1/2. It is believed

that the spin of the xi-hyperon is also 1/2, although it has been proved experimentally that it is a semi-integer. Naturally, the spins of antihyperons are the same as for hyperons.

The mode of disintegration of different hyperons and the relative probability of disintegration along different channels are given in Table 7. It is seen that

TABLE 7

HYPERON DISINTEGRATION CHANNELS

Particle	Mode of disintegration	Relative probability, %	Particle	Mode of disintegration	Relative probability, %
Λ^0	$p+\pi^-$	64	Σ^0	$\Lambda^0+\gamma$	100
	$n+\pi^0$	36	Σ^-	$n+\pi^-$	100
Σ^+	$p+e^-+\tilde{\nu}$	~ 0.2	Ξ^-	$\Lambda^0+\pi^-$	100
	$p+\pi^0$	50	Ξ^0	$\Lambda^0+\pi^0$	100
	$n+\pi^+$	50	Ω^-	$\Xi^0+\pi^-$	
	$p+\gamma$	~ 0.5			

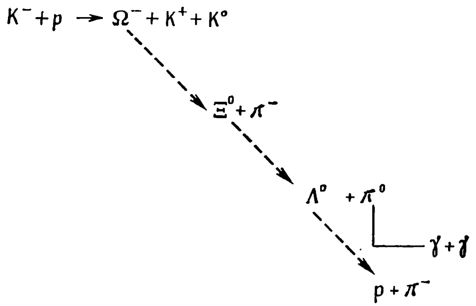
the sigma-zero-hyperon turns into a lambda and a photon, the disintegration being of an electromagnetic nature. Since we have familiarized ourselves with virtual processes, we should not be surprized to see that an electrically neutral particle emits a photon, i.e. an electromagnetic wave.

The time of disintegration of this kind should be very small. Theoretically, it is estimated at about 10^{-19} sec. It has been proved experimentally that it is less than 10^{-11} sec. The precise experimental value of the lifetime of the sigma-zero-particle is not known. The other hyperons disintegrate as a result of weak interactions. Table 7 shows that in each disintegration the strange number increases by unity. Since the charge

and the baryon number are retained on disintegration, the zeta-component of the isotopic spin changes by 1/2. Recalling the disintegration of K-mesons, in which the strangeness also changes by unity (it decreases for the K^+ and increases for the K^-), we can derive an experimental rule: in slow disintegration of strange particles the strangeness changes by ± 1, and the zeta component of the isotopic spin, by $\pm 1/2$. No exceptions from this rule have been observed so far. True, it is of little use, because the laws and nature of weak interactions are not very well understood as yet.

Table 7 also indicates that the xi-hyperon disintegrates only in one way: into a lambda- and a pi-meson. The simultaneous appearance of these particles and the measurement of their energy (mass) made it possible to establish the existence of the xi-hyperon. It is called a cascade hyperon since it disintegrates cascade-like, in steps: first a lambda appears, then it turns into non-strange particles. The cascade nature of this disintegration is due to the fact that strangeness cannot change by more than unity in one disintegration event.

The omega-minus-hyperon disintegrates in three stages, it can be called a three-cascade hyperon:



All particles, except the K^0-meson, which was found by its mass defect, are rigorously identified in this disintegration scheme, their energies are defined. The total energy of the reaction products (account being taken of the rest energy, mc^2) agrees well with the initial energy of the reacting particles.

Departing from the main subject for a moment, we will draw your attention to the following peculiarity: for K-mesons, as well as for pions, there is no law of conservation similar to the laws of conservation of leptons and baryons, which are strictly followed in any reaction, whether it is formation of new particles or disintegration. According to these laws, when a lepton appears or disappears, an antilepton also appears or disappears. The birth or disappearance of a baryon is also accompanied by the birth or disappearance of an antibaryon. The difference between the number of leptons and antileptons, as well as the difference between the number of baryons and antibaryons, does not change no matter how great either of them is. No such law exists for K-mesons or pions. The negative pion, the negative K- and neutral anti-K-meson, which are considered antiparticles relative to the positive pion and to the positive and neutral K-mesons, are in fact devoid of properties of antiparticles in many respects. Pi- and K-mesons may consist of matter and antimatter, as the photon can be called matter and antimatter simultaneously. The motion mass of any particle, an accelerated proton for instance, also possesses properties of matter and antimatter: pairs—particles and antiparticles—are born from it. Pi- and K-mesons also give birth to particles and antiparticles, they can, in a certain sense, be called energy quanta, quanta of a certain field. We believe that new investigations on the theory of elementary particles in this direction would be useful.

Of great importance is the question what role in the structure of matter is played by K-mesons and hyperons—strange particles. There is no answer so far.

The Soviet Academician M. Markov, as well as some foreign scientists, believes that hyperons are excited states of nucleons.

Hyperons appear when there is a large excess of energy. In ordinary matter surrounding us there is no need for hyperons.

Resonances

In recent years (beginning with 1960) whole classes of new particles have been discovered. These are so-called resonance particles (they are also called resonance states, or resonances), which disintegrate almost as rapidly as they form. Their lifetime is of the order of 10^{-22} sec. The resonances include the omega- and rho-mesons, which have been discussed above.

Despite their short lifetime, which practically excludes direct registration of resonances, physicists have succeeded in determining their mass, lifetime and other, even extremely detailed, characteristics. We will quote a pictorial example, which will help you understand the method for establishing the existence of a resonance particle and finding its mass. Let three identical balls, *1*, *2*, and *3*, bounce off each other under the effect of a definite force. Here, the law of conservation of angular momentum is observed. Therefore, if balls *2* and *3* bounce off in diametrically opposite directions with the same velocity, ball *1* will remain immobile, its kinetic energy being equal to zero. When balls *2* and *3* move in the same direction and with the same velocity, ball *1* will move in the opposite direction, its momentum will be equal

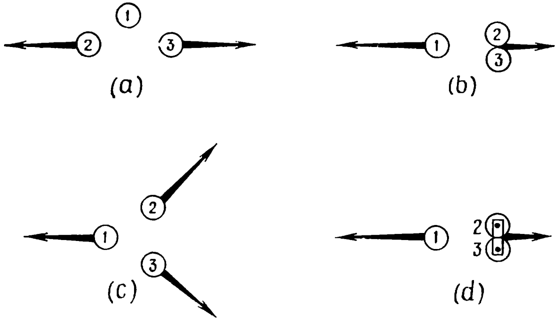


Fig. 38. In an imaginary experiment identical balls bounce off repeatedly under the effect of one and the same energy:

(a)—balls *2* and *3* bounce off in diametrically opposite directions with the same velocity, the energy of ball *1* being zero; *(b)*—balls *2* and *3* move together in a direction opposite to ball *1*, the energy of ball *1* being maximal; *(c)*—the balls bounce off at an angle to each other, the energy of ball *1* being between the maximal and minimal possible values; *(d)* — balls *2* and *3* are bound together, ball *1* always moving with a maximal energy.

to the total momentum of balls *2* and *3*, and its kinetic energy will be maximal. More often, intermediate cases occur, i.e. balls *2* and *3* bounce off at an angle to each other. Ball *1* will receive an intermediate kinetic energy between zero and maximum. Repeating the experiment many times and laying off the energy of ball *1* along one coordinate axis and the number of cases along the other, we obtain a smooth curve, similar to curve *1* in Fig. 39, which is called the phase curve. Then we join balls *2* and *3* together. Now they will move together with the same velocity; in any repeat experiment ball *1* will receive a maximal energy. In place of the smooth curve we shall have a stra-

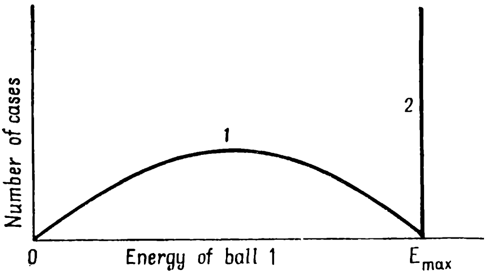


Fig. 39. Three balls bounce off under the effect of one and the same energy. The imaginary experiment is repeated many times. Curve *1* shows the number of cases when ball *1* has some energy or other. When balls *2* and *3* are bound together the energy of ball *1* is always the same (straight line *2*).

ight line *2*, corresponding to one and the same value of energy. If in repeat experiments balls *2* and *3* are joined together only in some cases, the smooth curve of energy distribution of the number of cases will have a peak referring to those cases when balls *2* and *3* are bound together. The joining of balls *2* and *3* is revealed by watching exclusively ball *1*, without any knowledge of the behaviour of balls *2* and *3*. Even if they are found lying separately after the experiment, one can say confidently that at the moment of collision they were bound together and separated only after some time.

In place of the energy of ball *1* one can lay off on the x-axis the total energy of balls *2* and *3* relative to the centre from which separation began. In this case, too, the curve will be smooth if the balls are not bound together. Otherwise the energy will be the same.

By measuring the impulses and energy of separated

particles, the mass of the resonance particle is found—the total mass of the joined balls *2* and *3* at the moment of their separation from ball *1*. The mass of a resonance particle is always larger than the sum of the masses of the particles into which it disintegrates. The mass of the joined balls *2* and *3* is larger than the mass of the separated balls *2* and *3* by the value of their kinetic energy (relative to the point of separation) divided by the square of the light velocity. To calculate the mass of a resonance particle, use is made of the laws of conservation of energy and momentum in the relativistic form. The law of conservation of rest mass does not embrace the theory of relativity. Instead, the law of conservation of energy operates which takes into account the rest energy of particles, m_0c^2.

The phase curve is often plotted by laying off on the x-axis, not the kinetic energy of a single particle (if there were three all in all), but the mass of two particles calculated in the manner described above. Then, if the particles are not bound together, a smooth curve is obtained, and if they are, a peak appears on the phase curve.

Suppose now we have five balls, and we suspect that balls *1-3* are bound together at the moment of separation and form a kind of a particle. This can be verified by summing up the impulses of balls *4* and *5* (or *1-3*) in each experiment and laying off along one axis the kinetic energy of balls *4* and *5* corresponding to the total impulse. If the distribution proves to be smooth, we are in error: balls *1-3* were not bound together at the moment of separation. If, however, the energy is the same, our supposition is correct: the balls were bound together into a kind of a particle at the moment of separation.

The omega-meson was found in a similar way. Those

cases of proton-antiproton annihilation were selected in which five pi-mesons appeared: two positive, two negative, and one neutral. By laying off along the x-axis the energy (mass) of three mesons the peak in the energy distribution of the number of cases was found. In actual practice the work is more complicated than would appear from the above description. Mesons have no numbers, one cannot distinguish them from one another, therefore it is necessary to try all the possible combinations and lay off along the x-axis not only the energy of mesons *4* and *5*, but also the total energy of mesons whose numbers would be *1* and *4* or *2* and *5*, etc., if they were known. The height of the peak over the phase curve decreases because of this, and to have it sharply defined the experiment has to be repeated many times "to accumulate statistics".

In each experiment, of course, one should make sure that the law of conservation of impulse is fulfilled. This work is very complicated and tedious, hundreds of thousands of experiments are made, but the method is based on the idea explained above with the aid of numbered balls.

The maximum in the energy distribution of the number of particles which characterizes the resonance is never very narrow (sharp). It is usually spread out, the resonance has a certain width, an "energy spread". Consequently, there is some uncertainty in its energy. Using the uncertainty ratio one can find the lifetime of a resonance, it is equal to the Planck constant divided by the energy uncertainty (the width of the resonance):

$$\tau = \frac{\hbar}{\Delta E} = \frac{\hbar}{\Gamma} \tag{19}$$

Thus, the width of the omega-resonance (one of the narrowest resonances) is 11.9 MeV. Hence, its lifetime

is $\tau = 1.05 \times 10^{-27}/11.9 \times 1.6 \times 10^{-6} = 5.5 \times 10^{-23}$ sec. More refined characteristics of resonances, such as spin, parity, and others, can be determined by using rather complicated methods, one of which was developed by R. Dalits of Chicago University (USA).

Incidentally, the term "resonance" as applied to elementary particles is quite logical. Over ten years ago (a large period for particle physics), when investigating interaction of pi-mesons with protons, scientists noted a very pronounced increase in the cross section of pi-mesons scattering from protons at a meson energy of about 200 MeV, and thus discovered a so-called resonance. Later on, this resonance, which had been predicted in 1952 by a group under the guidance of Enrico Fermi, became the famous Δ (1236,3/2$^+$)-resonance. It is sometimes called the nucleon isobar 3/2, 3/2. The two fractions mean that its isotopic and ordinary spins are equal to 3/2 each.

The theory of particle scattering from nuclei (including heavy ones) covers, among others, cases of resonance increase in the scattering cross section. The term "resonance scattering" is of quantum-mechanical origin. Resonance scattering occurs when the wavelengths characterizing the two particles coincide. Later on, when new particles were found, they were also named resonances, as well as the pion-proton resonance, which had proved to be a particle. This term has been firmly established, probably because by saying "resonance" or "resonance particle" one emphasizes the difference between it and the familiar elementary particle. Formerly this caution was quite justified. One could not assert with confidence that resonances were particles and not agglomerations of known particles. It is clear now, however, that most of the resonances are particles similar to the familiar elementary particles. Both are equally non-elementary.

There are resonances, however, of which one cannot state with full confidence that they are particles and not weakly bound agglomerations of other elementary particles.

The unity between the long-familiar elementary particles and resonances is confirmed by the fact that there is a certain intrinsic connection between them. As a rule, each strongly interacting elementary particle has resonances "of its own". Resonances differ from the familiar elementary particles by their higher mass. Their quantum numbers (spin, for instance) are also, as a rule, higher than those of the corresponding elementary particles. The increased mass and quantum numbers suggest that resonances are excited states of the corresponding elementary particles.

Table of Mesons and Mesic Resonances

The baryon number of mesic resonances, as well as mesons, is equal to zero. This distinguishes them from baryon resonances whose baryon number B is equal to $+1$. As they were discovered, resonances were given arbitrary symbols: ω, ρ, η, and others. Today information on resonances is arranged in a certain system and a new, more clear-cut and logically justified system of symbols is being introduced (voluntarily, of course), which will be easy to understand after inspection of the auxiliary table 8.

It can be seen that the new system is based on the hypercharge Y (which is equal to the sum of the baryon number and the strangeness) and the isotopic spin I. Each box contains resonances, denoted by a single symbol, with an identical hypercharge and iso-

TABLE 8

SYMBOLS FOR MESONS AND MESIC RESONANCES

I \ Y	$+1$	0	-1
0		η, φ	
1/2	K, K^*		$\widetilde{K}$, $\widetilde{K}^*$
1		π, ρ	

Note: Y = hypercharge, I = isotopic spin

topic spin. Thus, four resonances η, ω, φ, and f^0—have one and the same hypercharge (0), and isotopic spin (0). In place of the four different names which were used previously there are only two now: the η-resonance, or η-meson, if the G-parity of the particle is positive (+1), and the φ-resonance, if it is negative (—1). The particles differ in mass, therefore the symbol is accompanied by their mass value in megaelectron-volts.

It is well to recall once again that, strictly speaking, one cannot use megaelectron-volt or gigaelectron-volt units of energy to denote the mass value. The mass is equal to the energy divided by the square of the light velocity, and unit of mass should be one megaelectron-volt (gigaelectron-volt) divided by the square of the light velocity. When denoting the mass in electron-volts the physicists know this, of course, but still they use this unit, implying that the result should be divided by c^2. A conventional designation has been adopted which is also used here to get the reader accustomed to the widespread unit of mass. This convention has gained firm ground probably also because physicists often use a system of units in which the light velocity and the Planck constant are adopted

as the basic unit. In this system energy, impulse, and mass have the same dimensionality.

To convert the mass expressed in megaelectron-volts into grams one should convert the megaelectron-volts into ergs and divide the result by the square of the light velocity in square centimetres per square second. Thus the mass is equal to

$$\frac{938.3 \times 1.6 \times 10^{-6}}{(3 \times 10^{10})^2} = 1.67 \times 10^{-24}\mathrm{g}$$

In the particle designation its spin and parity are sometimes placed next to the mass expressed in MeV. For instance, for the omega-meson, the symbol φ' (783, 1^-) is adopted, while the rho-meson is denoted by ρ (770, 1^-). The unity with a minus above means that the particle spin is equal to unity and its parity is negative. Recall that if the wave function changes sign with a change in the sign of all space coordinates, it as antisymmetric. With a positive parity a change in the sign of the coordinates does not affect the sign of the wave function.

Improved designations of mesic (and baryon—which are treated in the next section) resonances will probably be adopted everywhere. Some of the most suitable old names, such as the omega-meson, however, will probably remain for a long time to come. In what follows they will be used along with the new ones.

Table 9, compiled on the basis of a survey by A. Rosenfeld and others (see *Rev. Mod. Phys.*, 39, No. 1, 1967), lists a couple of dozen meson resonances. But actually there are more. The isotopic spin, say that of π (1080), is equal to unity; this means that the table should list three resonances: positive, neutral, and negative, which differ in electric charge, in accordance with the three possible orientations of the isotopic spin in the conventional isotopic space (+1, 0 and —1).

TABLE 9

MESONS AND MESIC RESONANCES ($B = 0$)

Symbol and energy, MeV	Isospin I, G-parity, Spin J, Parity P, $I^G(J^P)$	Width Γ, MeV	Principal disintegration modes	Fraction, %
		Pion states		
η (548.6)	$0^+ (0^-)$	< 0.01	All neutral $\pi^+\pi^-\pi^0$ $\pi^+\pi^-\gamma$	75 25
φ' (783), ω	$0^- (1^-)$	11.9 (1.5)	$\pi^+\pi^-\pi^0$ $\pi^0 + \gamma$	90 9.7
η' (958)	$0^+ (0^-)$	< 4	3π $\pi^+\pi^-\gamma$	75 25
φ (1019)	$0^- (1^-)$	4	K^+K^- $K_1^0K_2^0$ $\pi^+\pi^-\pi^0$ (including $\pi\rho$)	48 40 12
η (1050), η_v	$0^+ (0^+)$	50	2π $K\tilde{K}$	< 70 30
η' (1250) f	$0^+ (2^+)$	117	2π $2\pi\ 2\pi$ $K\tilde{K}$	Many < 4 2.3
η' (1258), D	$0^+ (1^+)$	32 ± 8	$K\tilde{K}\pi$ $\pi_v (1003)\ \pi$	Predominantly
η (1420), E	$0^+ (0^-)$	76 ± 9	$K^*\tilde{K} + \tilde{K}^*K$ $\pi_v (1003)\ \pi$	50 50

Symbol and energy, MeV	Isospin I, G-parity, Spin J, Parity P, $I^G(J^P)$	Width Γ, MeV	Principal disintegration modes	Fraction, %
η (1500), f'	0^+ (2^+)	86 ± 23	2π $K\widetilde{K}$ $K^*\widetilde{K}+\widetilde{K}^*K$	<14 >60 <40
$\pi^{\pm}$ 139.58 π^0 134.98	1^- (0^-)	Stable to strong disintegrations		
$\rho^{\pm}$ (778) ρ^0 (770)	1^+ (1^-)	160 140	2π	~ 100
π (1003), π_v π (1080), $A1$	1^- (0^+) 1^- (1^+)	70 ± 15 130 ± 40	$K^{\pm}K^0$ $\rho\pi$	Many ~ 100
ρ (1210), B	1^+ (1^+)	119 ± 24	$\omega\pi$	~ 100
π (1300), $A2$	1^- (2^+)	81 ± 8	$\rho\pi$ $K\widetilde{K}$ $\eta\pi$	93 3.8 2.9
π (1640), 3π	$1^-(?)$	100 ± 20	3π $\rho\pi$ $K\widetilde{K}$	Probably predominates <40 40
ρ (1650)	1^+ $(?)$	150 ± 50	2π	Observed

Symbol and energy, MeV	Isospin I, G-parity, Spin J, Parity P, $I^G(J^P)$	Width Γ, MeV	Principal disintegration modes	Fraction, %
		K-meson states ($Y = +1$)		
K^+ 493.78 K^0 497.7 K^* (890), K^*	1/2 (0$^-$) 1/2 (1$^-$)	Stable to strong disintegrations 49.8 ± 1.7	$K\pi$	~ 100
K (1320), K_A	1/2 (?)	80 ± 20	$K^*\pi$ $K\rho$	Many
K (1420), K_v	1/2 (2$^+$)	92 ± 7	$K\pi$ $K^*\pi$ $K\rho$	52 36 9
K (1800), K_A	1/2 (?)	80 ± 20	$K\pi$ $K^*\pi$ K (1420) π $K\pi\pi$	< 10 35 ± 12 8 ± 5 40 ± 15

This is not done, just to save space. Readers familiar with the isotopic spin concept can easily determine the possible charge states of each of these particles. Besides the data given in Table 9 there are indications of the existence of non-strange resonances with masses of 410, 700, 973, 1410, 1440, 1700, 1930, 2200, and 2380 MeV, and also of K-meson resonances with masses of 725, 1080, 1175, 1215, and 1270 MeV.

Mesic resonances with a hypercharge of $Y=0$ have no antiparticles. η- and φ-resonances have no antiparticles either, while for π- and ρ-resonances, whose

isotopic spin is unity, the negative particle is considered an antiparticle relative to the positive one, and the neutral particle coincides with its antiparticle. Resonances with $Y=+1$ have antiparticles, their hypercharge Y (for mesons it coincides with strangeness) being equal to —1. As a result, if we add up all the charge states of the particles listed in Table 9 and recall the antiparticles (where they exist) the table will contain about 70 meson resonances.

All meson resonances disintegrate as a result of strong interaction, therefore the law of conservation of strangeness holds good in disintegration. Disintegration of strange meson resonances is always accompanied by the birth of a K-meson, whose strangeness is equal to that of the initial resonance.

Several resonances with a mass of about 1200 MeV are known which cannot be fitted into the classification so far. It is significant that some of them disintegrate into a meson and a mesic resonance. They include the $A2$-resonance with a mass of 1300 MeV and a width of about 80 MeV disintegrating into a pi-meson and a rho-resonance.

Above, we mentioned resonances disintegrating into two or three mesons. There are also four-pion resonances. We know of a B-resonance disintegrating into a pi-meson and an omega-meson (i.e. into four pi-mesons in the final analysis). The mass of the B-resonance is equal to 1.21 GeV, its width is $\Gamma \simeq 100$ MeV, the spin and parity being 1^+. The B-meson is also called the Buddha-meson. It was discovered in collaboration with a scientist from South Vietnam when Buddhist monks burned themselves to death in protest against foreign aggression.

In the middle of 1964 a five-pion resonance was discovered, which disintegrates into an omega-meson and two pi-mesons. The number of multiparticle mesic

resonances continues to grow and so does their diversity.

It is interesting to note that mesic resonances like to appear together with baryonic resonances. Thus, in the reaction of formation of an omega-meson by the scheme

$$\pi^+ + p \rightarrow \pi^+ + p + \omega$$

in 40 per cent of the cases a baryonic Δ-resonance disintegrating into a proton and a positive pi-meson is born together with the omega-meson. Incidentally, spurious resonances are beginning to appear along with true ones. An example of a spurious resonance is the so-called *ABC*-resonance resulting from the reaction

$$p + d \rightarrow \mathrm{He} + 2\pi$$

The energy of a two-pion system "pretending" to be a resonance is about 310 MeV, its width $\Gamma = 16$ MeV. The *ABC*-resonance received its name from the initial letters of the names of scientists who discovered it (A. Abashin, N. Booth, and K. Crow). Spurious resonances are not due to some mistake in experiment, nor, of course, to evil intentions. They result from a very subtle effect that sometimes yields a peak on the phase curve which is taken for a resonance. When the kinetic energy and, accordingly, the velocity of scattering particles are small, the particles remain for a rather long time within the range of the nuclear forces of neighbouring particles. One of three particles may be connected with another somewhat longer than with the third, and therefore a peak appears on the phase curve. It is sufficient to increase the energy of colliding particles giving rise to three scattering particles, and the relative velocity of separation increases, the "sticking" ceases, and the peak on the phase curve

disappears. In contrast to spurious resonances, true ones do not disappear with an increase in the energy of the interacting particles.

Table of Baryons and Baryonic Resonances

The baryon number of all baryonic resonances is $B=+1$. For the corresponding antiparticles (antibaryonic resonances) it is equal to -1. Nucleon resonances ($Y=+1$) were formerly denoted by a nucleon symbol with an asterisk (N^*). When their number had increased, too many asterisks had to be used, and therefore superscripts were introduced. Resonances with a hypercharge equal to that of the lambda- and sigma-hyperons ($Y=0$) were denoted by the letter Y, which also had asterisks and superscripts. It was found more convenient and logical to use a classification according to the hypercharge and isotopic spin as given in the auxiliary table 10. The mass, spin, and parity are placed, as in the case of mesic resonances, in brackets after the symbol. Resonances with a hypercharge of $Y=-2$ (strangeness $S=-3$) have not been observed so far. The designations of resonances for hyperons given in Table 10 coincide with those used for comparatively long-lived baryons. They are marked as stable ones in Table 11 (stability with respect to strong disintegrations is implied).

The baryons and baryonic resonances given in Table 11 are classified into four groups according to the hypercharge: $Y=+1$, $Y=0$, $Y=-1$, and $Y=-2$. Disintegration of first-group resonances (nucleon resonances) always produces a nucleon, this is required by the laws of conservation of the baryon charge and

TABLE 10

SYMBOLS FOR BARYONS AND BARYONIC RESONANCES

I \ Y	+1	0	−1	−2
0		Λ lambda		Ω omega
1/2	N nucleon		Ξ Xi	
1		Σ sigma		
3/2	Δ delta			

Note: Y = hypercharge, I = isotopic spin

strangeness. A second-group zero hypercharge corresponds to a strangeness of —1. The disintegration products of this group inevitably include a particle with a strangeness of —1. This may be a lambda-hyperon, sigma-hyperon or anti-K-meson. In the last case, a nucleon should also appear according to the law of conservation of the baryon number. In most cases disintegration products contain a lambda- or sigma-hyperon. The third group is known to contain two resonances so far, they disintegrate into a xi-hyperon and a pi-meson. For Λ and $\widetilde{K}$ the strangeness and hypercharge of the disintegration products are equal to those of the initial resonance.

The fourth group, discovered recently, contains only one stable particle, the omega-minus-hyperon. No resonances with a hypercharge of —2 (strangeness minus 3) have been discovered as yet.

TABLE 11

BARYONS AND BARYONIC RESONANCES*

Symbol and energy, MeV	Isospin I, Parity P, Spin J $[I\ (J^P)]$	Width Γ, MeV	Principal disintegration modes	Fraction, %
		Nucleon states ($Y = +1$)		
p (938.3) n (939.6)	1/2 ($1/2^+$)	Stable to strong disintegrations	—	—
N (1400)	1/2 ($1/2^+$)	200	$N\pi$	70
N (1525)	1/2 ($3/2^-$)	105	$N\pi$ $N\pi\pi$ Δ (1236) π	65 35 20
N (1570)	1/2 ($1/2^-$)	130	$N\pi$ $N\eta$	30 70
N (1670)	1/2 ($5/2^-$)	140	$N\pi$ $N\pi\pi$	40 Predominates
N (1688)	1/2 ($5/2^+$)	110	$N\pi$ $N\pi\pi$	65 Predominates
N (2190)	1/2 ($7/2^-$)	200	$N\pi$ ΛK	30 ?
N (2650)	1/2 ($11/2^-$)	~ 300	$N\pi$ ΛK	7 ?
Δ (1236)	3/2 ($3/2^+$)	120	$N\pi$	100

Continued

Symbol and energy, MeV	Isospin I, Parity P, Spin J [I (J^P)]	Width Γ, MeV	Principal disintegration modes	Fraction, %
Δ (1670)	3/2 ($1/2^-$)	180	$N\pi$ $N\pi\pi$	40 ?
Δ (1920)	3/2 ($7/2^+$)	200	$N\pi$ ΣK	50 Perceptible
Δ (2420)	3/2 ($11/2^+$)	275	$N\pi$ ΣK	10 ?
Δ (2850)	3/2 ($15/2^+$)	$\sim$ 300	$N\pi$	3
		Hyperon states ($Y = 0$)		
Λ (1115.6)	0 ($1/2^+$)	Stable to strong disintegrations		
Λ (1405)	0 ($1/2^-$)	35	$\Sigma\pi$	100
Λ (1520)	0 ($3/2^-$)	16 ± 2	$N\tilde{K}$ $\Sigma\pi$ $\Lambda\pi\pi$	39 ± 5 51 ± 6 10 ± 2
Λ (1670)	0 ($1/2^-$)	18	$\Lambda\eta$ $N\tilde{K}$	? ?
Λ (1700)	0 ($3/2^-$)	40 ± 10	$N\tilde{K}$ $\Sigma\pi$	20 Perceptible
Λ (1820)	0 ($5/2^+$)	83 ± 8	$N\tilde{K}$ $\Sigma\pi$ Σ (1385) π	70 11 18

Continued

Symbol and energy, MeV	Isospin I, Parity P Spin J $[I\ (J^P)]$	Width Γ, MeV	Principal disintegration modes	Fraction, %
Λ (2100)	0 (7/2$^-$)	160	$N\widetilde{K}$ $\Sigma\pi$	29 Perceptible
Λ (2340)	0 (?)	105	$N\widetilde{K}$	10
Σ^+ (1189.5) Σ^0 (1192.6) Σ^- (1197.4)	1 (1/2$^+$)	Stable to strong disintegrations		
Σ (1385)	1 (3/4$^+$)	37 ± 3	$\Lambda\pi$ $\Sigma\pi$	91 ± 3 9 ± 3
Σ (1660)	1 (3/2$^-$)	50	Λ (1405) π $\Sigma\pi$ $\Lambda\pi$	Many ? ?
Σ (1770)	1 (5/2$^-$)	89 ± 12	$N\widetilde{K}$ $\Lambda\pi$ Λ (1520) π Σ (1385) π	49 17 19 12
Σ (2035)	1 (7/2$^+$)	160	$N\widetilde{K}$ $\Lambda\pi$	16 25
Hyperon states ($Y = -1$)				
Ξ^0 (1314.7) Ξ^- (1321.2)	1/2 (1/2$^+$)	Stable to strong disintegrations		
Ξ (1530)(0) 1528.9 (—) 1533.8	1/2 (3/2$^+$)	7.3 ± 1.7	$\Xi\pi$	~ 100

Symbol and energy, MeV	Isospin I, Parity P, Spin J $[I\ (J^P)]$	Width Γ, MeV	Principal disintegration modes	Fraction, %
Ξ (1815)	1/2 (?)	16 ± 8	$\Lambda\widetilde{K}$ $\Xi\pi$ $\Xi\pi\pi$ Ξ (1520) π	$\sim$ 65 16 25 $\sim$ 20
Hyperon states $(Y = -2)$				
Ω^- (1674)	0 (3/2+)	Stable to strong disintegrations		

* See *Rev. Mod. Phys.* 39. No. 1, 1967.
Note: There are indications of the existence of resonances z_0 (1865), $(Y=+2)$, N (1700), N(3030) Δ(3230), Σ(1910), Σ(2260), Ξ(1930), etc.

Among the nucleon resonances there are particles with an isotopic spin of 3/2; these are Δ-resonances. Recalling equation (16) we see that the isotopic spin projection values 3/2, 1/2, $-1/2$, and $-3/2$ are associated with electric charges (in proton charge units) of $+2$, $+1$, 0, and -1. Each of the Δ-resonances thus can be in four different charge states. Here we encounter for the first time elementary particles having a doubled proton charge.

In all, Table 11 lists 66 particles, taking into account the different charge states. Since each of them has an antiparticle, we can find the total number of baryons and baryonic resonances, which is equal to 132. Adding 70 mesons and mesic resonances, we obtain the total number of particles given in Tables 9 and 11, about 200 altogether. The tables do not include all resonances, however: some dubious and multi-pion

resonances are omitted. The number of known resonances continues to grow. The total number of particles, including stable and comparatively long-lived ones, has already considerably exceeded 200. Their systematization has become a matter of urgency. The following four sections deal with this subject.

On the Classification of Hadrons

It has not been possible yet to classify all elementary particles and resonances according to a single scheme, a unified principle. In the first place, leptons (both types of neutrino, the electron, the muon and their antiparticles) drop out of the general system. There is a rather orderly classification of mesons, baryons, mesic and baryonic resonances, i.e. strongly interacting particles. L.Okun, Corresponding Member of the USSR Academy of Sciences, has suggested combining them all under the head "hadrons", which is the Greek for big, massive, to distinguish them from the light particles, leptons. Thus, we will now deal with the classification of hadrons. But we will have to go back to 1956 when the Japanese scientist S. Sakata proposed a scheme for classification of mesons and baryons; no resonances were actually known at the time.

According to the Sakata model there are three privileged — fundamental — baryons (proton, neutron and lambda-hyperon) of which (including their antiparticles) all mesons and baryons are built. In the Sakata scheme each meson consists of one fundamental particle merging with a fundamental antiparticle. They are bound together so strongly that the mass defect is close to the sum of the masses of the two baryons. Recall

that the mass defect multiplied by the square of the light velocity is equal to the binding energy. The positive pi-meson consists of a proton and an antineutrino, the negative one, of a neutron and an antiproton. The positive K-meson consists of a proton and an antilambda-hyperon, the negative one, of an antiproton and a lambda-hyperon. Neutral mesons have a somewhat more complicated structure. The baryon charge of any one of the above mesons is equal to zero; the other quantum numbers, such as the isotopic spin and strangeness, are integers as well.

According to this scheme each baryon consists of three particles (it is often said that it consists of three fields to emphasize the fact that the fundamental particles—fields—differ in some way or other from the particles observed in experiment), namely two fundamental baryons and one antibaryon, the antibaryon consisting of two fundamental antibaryons and one baryon. Thus, for instance, the positive sigma-hyperon consists of a proton supplying it with electric charge, a lambda-hyperon imparting to it the necessary strangeness, and an antineutron making up the baryon-number balance. All baryons are built in a similar way.

The three fundamental baryons in the Sakata model form one isotopic doublet (p, n) and one isotopic singlet (Λ). Using any three strongly interacting particles of which two form an isodoublet and one an isosinglet, it is possible to construct a model similar to Sakata's and obtain correct quantum numbers for mesons and baryons. There are several such models, which do not differ from Sakata's model in principle.

In the hey-day of Sakata's model scientists discovered a correspondence between the three fundamental baryons and the three leptons: neutrino, electron, and negative mu-meson; there was a certain symmetry

between the fundamental strongly interacting particles and the fundamental weakly interacting ones; it was named the Kiev symmetry since it had first been proposed at the Kiev International Conference on High-Energy Physics in 1959.

Scientists began to hope that they would be able to systematize all particles (both hadrons and leptons) and even deduce some universal law of nature which found expression in the Kiev symmetry. But soon afterwards a fourth lepton was discovered which upset the Kiev symmetry, it was the meson neutrino; then the optimism began to subside. After the appearance of a multitude of resonances which, as well as the "old" mesons and baryons, had to be fitted into the classification scheme, Sakata's model began losing in popularity since; it was often disproved by experiment. It was finally supplanted by the model of Gell-Mann and Ne'eman, who had worked it out in 1961 independently of each other.

In the new model mesons and baryons form according to a scheme similar to Sakata's. However, in place of the three privileged baryons the authors adopted the whole octet of "old" baryons as fundamental particles: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^-, Ξ^0. Each meson "consists" of a baryon and an antibaryon. But the new scheme contains many more fundamental baryons than Sakata's model. Therefore, their combination yields many more meson states than are actually observed in experiment.

To form baryons according to the new scheme, eight fundamental baryons are taken and manipulated together with eight "principal" mesons so as to form meson-baryon pairs. As a result a rather wide assortment of possible baryons is obtained which are distributed over so-called supermultiplets. In the next section the new system of hadrons is considered in

more detail. It is definitely more democratic than Sakata's model. The number of priveleged particles is not restricted to three baryons, but all the eight known, relatively long-lived baryons with a spin of 1/2.

Using a "poetical license", we can say that democracy is one of the strongest sides of any physical theory aimed at revealing the basic laws of nature. For instance, the special theory of relativity proclaims the "democratic" equality of all inertial (non-accelerated) reference systems. Giving preference to any one reference system (earth, sun, etc.) introduces an element of subjectivity into mechanics. Choosing some hadrons as privileged ones and thus violating the principles of democracy, one may create a degree of arbitrariness, a sort of subjectivity.

Unitary Symmetry. Gell-Mann-Ne'eman Model

In order to describe the new model we must introduce the rather complicated concept of unitary symmetry. We will also have to approach it gradually.

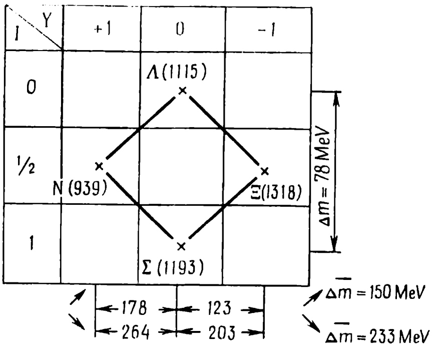
Nuclear forces, as you already know, are the same for protons and neutrons. Therefore the proton and the neutron are considered to be one and the same particle residing in different charge states. They are identical except for the electric charge. The difference in their masses is due to the difference in charge. Similarly, any one of the isotopic multiplets is a particle which may be in different charge states. If all particles could be deprived of their electric charges, they would be completely undistinguishable within each isotopic multiplet: the proton would be identical to the

neutron, the three pi-mesons would be absolutely identical, the three sigma-hyperons would be undistinguishable, etc. The isotopic multiplets would be degenerated with respect to the isotopic spin components. An electric charge and the associated electromagnetic interactions cancel degeneration, they split the isotopic multiplet and give a definite identity to each of the charge states. So far we have dwelt on the isotopic multiplet. Now we can pass over to a more complex, unitary multiplet, or, as it is sometimes called, the supermultiplet. It consists of several isotopic multiplets differing either in strangeness or in isotopic spin, or both. Due to unitary symmetry, particles of different strangeness and different isotopic spins are identical in one and the same unitary multiplet. Thus, an octet of old baryons consisting of four isotopic multiplets is contained in a single unitary multiplet as shown in Table 12. A hypercharge which exceeds strangeness ($Y=B+S$) by unity for baryons, is taken here instead of strangeness. The table demonstrates the validity of a certain generalized Pauli principle: each of the four isotopic multiplets contained in a supermultiplet differs from the others either in hypercharge or in isotopic spin. Within each of the isotopic multiplets the particles differ in electric charges and the components of the isotopic spin.

From the standpoint of unitary symmetry all particles in the hyperon octet given in Table 12 are entirely undistinguishable, they are identical. In actuality, of course, they differ in mass, isotopic spin, and hypercharge. But this difference is due to a moderately strong interaction, of which we know practically nothing but which imparts to each hadron its hypercharge and isotopic spin and consequently does not change the mass to any considerable extent. The modera-

TABLE 12

UNITARY OCTET, $J^P = 1/2^+$



tely strong interaction removes degeneration with respect to the hypercharge and isotopic spin. It splits the unitary multiplet into several isotopic multiplets as shown in some of the following tables, including Table 12.

What distinguishes one unitary supermultiplet from another? The hypercharge and isotopic spin have lost their meaning, they appear only in a moderately strong interaction. What remains is the spin, parity, and mass of the particle. Spin and parity of all particles within the supermultiplet must be identical, of course. Indeed, the particles within the supermultiplet are undistinguishable until a moderately strong interaction occurs, which imparts to them a specific hypercharge and isospin. Their mass is not known precisely because it differs slightly even within a single multiplet when it is split (and we observe only such multiplets). Therefore, one should speak only of the order of magnitude of the mass in each supermul-

tiplet, more precisely, of its "average" value, although we are not familiar with the law of averaging. There is also a baryon number, but it is not characteristic of a separate unitary multiplet. This number splits the multiplets into two groups: meson unitary multiplets (baryon number zero) and baryon unitary multiplets (baryon number $+1$).

Thus, mass, spin, and parity appear to be more profound and stable characteristics of elementary particles than the isotopic spin and hypercharge (or rather strangeness), which disappear in the case of unitary symmetry, i.e. on degeneration of the supermultiplet. The mass is considered to be the most important characteristic. It is called the principal quantum number and distinguishes one supermultiplet from another. The average masses of different supermultiplets would be expected to differ from each other by a value exceeding the difference of masses within the unitary multiplet. In other words, the splitting of a unitary multiplet with respect to mass due to a "moderately strong" interaction must be less than the difference in mass between two adjacent unitary multiplets. In actual practice, however, this law is obeyed very rarely.

How many isotopic multiplets and of what type can a unitary supermultiplet contain? What types of unitary multiplets are possible and how many types are there altogether? To answer these questions use was made of the group theory, one of the most interesting and abstract branches of higher algebra. The group theory determines the transformations of various values. In quantum mechanics, operations with real particles are associted with so-called unitary transformations. From among the existing groups, SU_n were selected, which refer to unitary transformations. Which of them should be chosen? Experi-

ment supplied the answer. Supermultiplets allowed by different groups were determined. One of them, SU_3, yielded the best agreement with experiment. Two models were compared with experiment, those of Sakata, and Gell-Mann-Ne'eman. Sakata's model also yields particles with different values of isotopic spin and hypercharge, they can be combined into unitary multiplets as well. The supermultiplets obtained were compared with the supermultiplets allowed by the Gell-Mann-Ne'eman model. It turned out that Sakata's model yields a unitary singlet and a unitary octet

$$3\times 3=1+8$$

for mesons.

For baryons, the model leads to the existence of unitary multiplets of three, six and fifteen particles

$$3\times 3\times 3=27=3+3+6+15$$

In the Gell-Mann-Ne'eman model the following supermultiplets are possible both for mesons and baryons: a unitary singlet, two octets, a decaplet, a conjugate decaplet and a multiplet of 27 hadrons. Accordingly, they contain the following numbers of particles:

$$8\times 8=64=1+8+8+10+\overline{10}+27$$

Figure $\overline{10}$ represents a conjugate decaplet. Since the new model was in better agreement with experiment it was finally accepted*.

Now we will consider particle distribution within supermultiplets. We are already familiar with the octet (see Table 12). Table 13 shows a decaplet, it is

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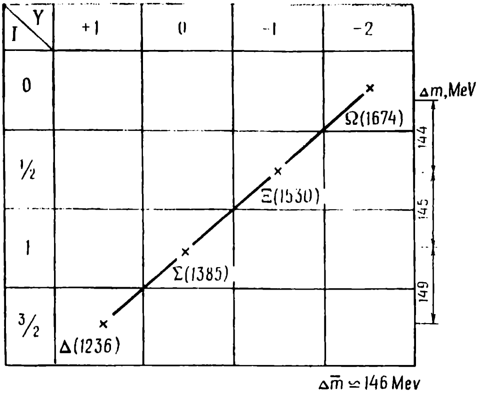
* In 1964 another classification of hadrons was published; it was based on the so-called $SU(6)$-symmetry [*The Physical Review Letters*, 13, No. 5, 173 (1964)].

TABLE 13

UNITARY DECAPLET, $J^P = 3/2^+$



characterized by a spin of 3/2 and positive parity. The parity is denoted by a sign at the upper right of the spin: $3/2^+$. The delta-, sigma-, and xi-resonances (resonance isotopic multiplets) listed in Table 13 were known earlier. They totalled up to nine particles. One more particle—an isotopic singlet with a strangeness of —3 (hypercharge —2)—was bound to exist. Noting that the mass of a particle increases from cell to cell by about 150 MeV as the absolute value of strangeness increases (as it moves up and to the right along the diagonal) scientists predicted the mass of the omega-hyperon. We already know that the omega-hyperon was indeed discovered later on. This great achievement in the new hadron classification soon gained universal recognition.

Tables 12 and 13 representing a unitary octet and decaplet contain four isotopic multiplets each of which is regarded as a single particle. But electric charges

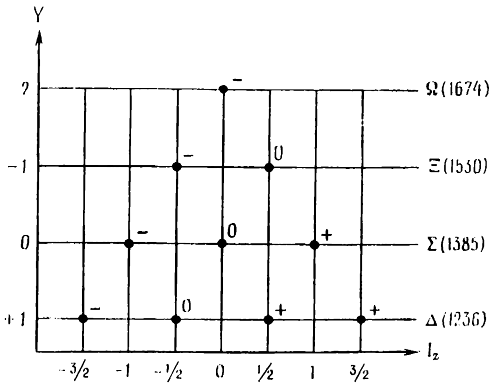


Fig. 40. Unitary decaplet, $J^P=3/2^+$. The four isotopic multiplets contained in the decaplet are split according to the magnitude of the isotopic spin component along the third "axis". The picture shows the composition of each multiplet.

remove degeneration in isomultiplets, and therefore each of the isomultiplets splits into elementary hadrons. Unitary multiplets (supermultiplets) are often represented as consisting of elementary hadrons and not of isomultiplets, as is done in Table 12, 13, and so on. In this case the characteristic features of unitary symmetry are somewhat vague (it is not separated from the charge independence of nuclear forces, from the isotopic symmetry). But the terms "octet" and "decaplet" become obvious immediately: the number of hadrons in each of the supermultiplets can be counted directly in the picture. The decaplet (Fig. 40) looks particularly pictorial: it represents an isosceles triangle whose base is made up of four hadrons forming a Δ-resonance. The next row contains three Σ-resonances, then two Ξ's, with an Ω-resonance at the apex.

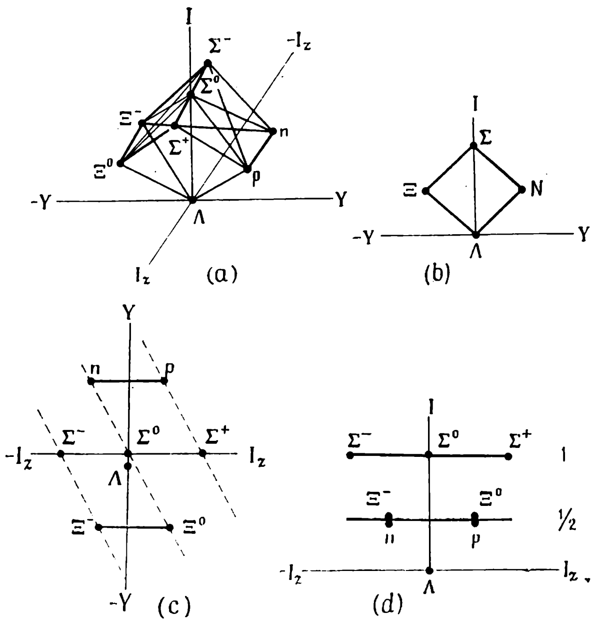


Fig. 41. Unitary baryon octet: *(a)*—three-dimensional representation; *(b)*, *(c)*, *(d)*—projections onto different planes.

By laying off the values of the hypercharge (x-axis), the zeta-component of the isotopic spin (y-axis), and the isotopic spin (z-axis) one can construct a three-dimensional representation of any unitary multiplet. Figure 41*a* shows a unitary baryon octet. The projection of this figure onto the plane *Y-I* (Fig. 41*b*) yields a familiar combination—four isomultiplets comprising a unitary octet. Here, the unitary octet is degenerated along the zeta-component of the isotopic spin: all the

particles are devoid of electric charges, or, more precisely, the latter are neglected.

The projection onto the plane Y-I_z (Fig. 41*c*) is also familiar. It yields a considerable amount of information. Isotopic multiplets are located on each of the horizontal lines. Along the inclined lines lie particles having identical electric charges and differing only in unitary properties. The inclined lines pass through particles with an identical unitary spin, but with a different projection of it onto a certain direction in a conventional unitary space (one more space!). The unitary spin of the pair p, Σ^+, as well as that of the pair Σ^-, Ξ^-, is equal to 1/2. The unitary spin of the triplet (n, Σ^0, Ξ^0) is equal to unity.

The projection of a unitary octet onto the plane I_z-I (Fig. 41*d*) is also of interest. An octet degenerated with respect to the hypercharge would look like that.

The electric charge introduces only relatively small differences into the nuclear properties of elementary particles. Therefore, when we deal with unitary symmetry, this charge can be neglected, and we can consider the projection of the unitary multiplet onto the plane Y-I, as was done above in the tables containing unitary multiplets. There is a theoretically substantiated rule according to which supermultiplets recur at a given parity, when the spin increases by 2. Therefore an octet with a spin of $1/2^+$ should be matched by an octet with a spin of $5/2^+$, and a decaplet with a spin of $3/2^+$, by a decaplet with a spin of $7/2^+$. With the aid of this rule one can accommodate several more baryonic resonances in the unfilled supermultiplets (Tables 14 and 15).

The reader may ask: how is it that the spin of a baryon may be equal to 5/2 or 7/2? Each of the fundamental baryons has a spin of 1/2. Three particles

TABLE 14

UNITARY SUPERMULTIPLET, $J^P = 5/2^+$

I \ Y	+1	0	−1
0		Λ(1820)	
½	N(1688)		Ξ(?)
1		Σ(1910)	

TABLE 15

UNITARY DECAPLET, $J^P = 7/2^+$

I \ Y	+1	0	−1	−2
0				Ω(?)
½			Ξ(?)	
1		Σ(2035)		
$^3/_2$	Δ(1920)			

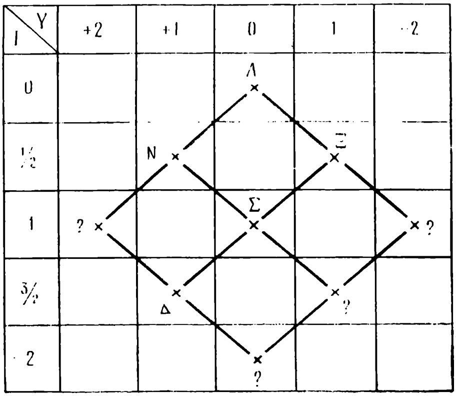
Note: Only two isotopic multiplets contained in this supermultiplet are known.

may have a total spin of 3/2 at the most. Where do we get the additional momenta of 1 and 2 necessary to obtain the final momenta of 5/2 and 7/2?

When three fundamental baryons are combined into a single ordinary one, the fundamental baryons may have a non-zero orbital momentum. For instance, one of them may be in the *p*-state (orbital momentum unity). If this momentum is parallel to the total spin (3/2), the momentum of the final particle will be equal to 5/2. Momenta of 7/2, 9/2, and so on, are obtained in a similar way. A large total spin of a particle by no means indicates that it is compound and that one of the particles within it has an orbital momentum. The total momentum of the particles comprising a baryon transforms into the proper momentum (spin) of the final particle. The particle as a whole "rotates" with such a large momentum.

TABLE 16

UNITARY MULTIPLET OF 27 HADRONS ($B = +1$)



A diagram of a supermultiplet of 27 baryonic resonances is depicted in Table 16. At present we cannot assign any real hadrons to this multiplet with sufficient confidence. Therefore an opinion has been voiced that this multiplet is non-existent. If, however, it is found to exist, then the diversity of observed resonances will increase considerably. An isotopic quintet ($I=2$, $Y=0$) will appear. There will be two isotriplets symmetric with respect to the charged states: the electric charges of one will be equal to $+2$, $+1$, and 0, and those of the other, to 0, -1, and -2. Four of the 27 isotopic multiplets comprising the supermultiplet have no symbols as yet. By the way, the Greek alphabet has four capital letters available which have not been used to denote elementary particles and which differ in their shape from Latin letters, namely Θ, Γ, Φ, Ψ. They could be used to denote the new isotopic multiplets predicted by the unitary symmetry (by supermultiplet 27).

TABLE 17

UNITARY DECAPLET OF PARTICLES AND UNITARY CONJUGATE DECAPLET OF ANTIPARTICLES

I \ Y	$+2$	$+1$	0	-1	-2
0	$\tilde{\Omega}$				Ω
$1/2$		$\tilde{\Xi}$		Ξ	
1			$\tilde{\Sigma}$ Σ		
$3/2$		Δ		$\tilde{\Delta}$	

It now remains to tell you about the unitary singlet; the hyperon resonance Λ (1405) is usually implied. Table 11 still contains many loose resonances which cannot yet be assigned to any unitary multiplet.

Many people think that the conjugate decaplet is not associated with any real particles, but Table 17 convincingly demonstrates that it is matched by the antiparticles of those particles which are contained in the ordinary decaplet. The octet of antiparticles coincides with the octet of particles. Here, too, a complete symmetry is observed (Table 18). There is

TABLE 18

OCTETS FOR PARTICLES AND ANTIPARTICLES

I \ Y	+1	0	−1
0		Λ × $\tilde{\Lambda}$	
1/2	N $\tilde{\Xi}$ ×		× Ξ $\tilde{N}$
1		Σ × $\tilde{\Sigma}$	

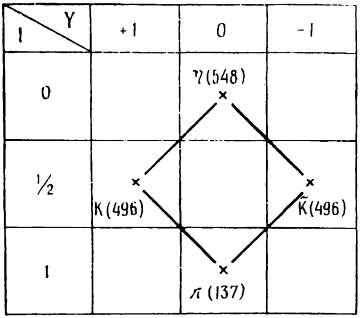
a certain difference, however. The box containing a nucleon receives an antixi-hyperon instead of an antinucleon. The antinucleon occupies the site of the xi-hyperon. To obtain an octet of antibaryons, the octet of corresponding baryons should be turned through 180° about the vertical axis and the particle symbols should be replaced by antiparticle symbols. The same

method can be used to obtain a supermultiplet for 27 antiparticles. In either case antiparticles with a zero hypercharge will of course remain in the same boxes where the respective particles reside.

The hadrons with a baryon number $B=0$ (mesons and mesic resonances) are divided into two octets. The first (Table 19) includes the previously known

TABLE 19

MESIC OCTET, $J^P = = 0^-$ (IT INCLUDES "OLD" MESONS: π, K, AND $\widetilde{K}$)



pi- and K-mesons and the eta-resonance. The second octet (Table 20) consists of K- and ρ-resonances, and also of a resonance representing an isotopic singlet. It is not clear yet what kind of resonance it is: it could be φ' (783)—an omega-meson or φ (1019)—a phi-meson. A mesic octet with both a spin and a parity of 2^+ is possible; it consists of η' (1250), π (1300), K(1420) and $\widetilde{K}$(1420). No mesic resonances corresponding to a decaplet and a unitary multiplet of 27 particles have been observed.

Finally, a few words on terminology. Gell-Mann and Ne'eman called their model of supermultiplets "The

TABLE 20

MESIC OCTET, $J^P = 1^-$

I \ Y	+1	0	-1
0		$\varphi'(783)$ or $\varphi(1019)$	
$1/2$	$K(890)$		$\bar{K}(890)$
1		$\rho(770)$	

Eightfold Way". This name implies three different octets. The first one represents eight quantum numbers, which are dealt with when considering each of the supermultiplets: three isotopic spin components, a hypercharge (strangeness), and another four quantum numbers, which have no name and are associated with "moderately strong" interaction. Two of these numbers change the hyperon number by ± 1 without changing the electric charge, the two others* change the hypercharge by $\pm$ 1 and simultaneously change the electric charge by ± 1. The second octet may be associated with some kind of superstition or with the sense of humour of the authors of the model. In connection

* The first two numbers are the two values of projections of the unitary U-spin onto the "zeta-axis" which change by ± 1, the other two, the values of the projection onto the same axis of the V-spin which also change by ± 1.

with their investigation they recalled Buddha's alleged pronouncement about the eight true roads which one should travel to relieve one's sufferings. And, finally, the third octet represents the eight fundamental baryons forming the basis of the model.

Quarks

Along with the logical orderliness and "democratic nature" of the Gell-Mann-Ne'eman model it has some faults as well. One of them is the prediction of a unitary multiplet of 27 hadrons and also of a conjugate decaplet ($\overline{10}$), which have not been observed in experiment for mesons and mesic resonances. The conjugate decaplet corresponds to the antiparticles of those particles which belong to the baryon decaplet. There are no serious grounds to believe, either, that a supermultiplet of 27 baryons can be filled. The considerations about the disadvantages of the Gell-Mann-Ne'eman model may be rather rash, at least as regards baryons. But a new model has been constructed which has unitary multiplets of baryons consisting of 1, 8, and 10 particles and having no conjugate decaplet and a multiplet of 27 baryons. For mesons, the new model yields a unitary singlet and a unitary octet. The new model, which was published by its author Gell-Mann on February 1, 1964, is a step forward from the Sakata model. As in the latter, the fundamental particles are an isotopic doublet with a zero strangeness and an isotopic singlet with a strangeness of -1. However, these fundamental particles, which Gell-Mann named quarks, do not coincide with any one of the known hadrons. The quarks are a kind of primordial matter. Any meson consists of a quark and an antiquark, while any baryon consists of three

quarks. Antiquarks do not form any part of baryons. Each antibaryon consists of three antiquarks.

Since quarks, of which all hadrons consist, are absolutely unlike any of the observed particles, none of the hadrons has any advantages over the others, the quark model is "the most democratic".

All quarks have the same spin of 1/2 and the same baryon charge of 1/3. But then some differences begin to appear. The first two quarks, whose strangeness is zero, form an isotopic doublet with electric charges of +2/3 and —1/3 of the proton charge. Strangeness of the third quark (which is an isosinglet) is —1 and its electric charge, —1/3. The quark mass is not known, but it cannot be small. The properties of quarks are given in Table 21.

TABLE 21

PROPERTIES OF QUARKS

Quark	Spin	Baryon charge	Strangeness	Hypercharge	Isospin	Electric charge
q_1	1/2	1/3	0	1/3	1/2	+ 2/3
q_2	1/2	1/3	0	1/3	1/2	— 1/3
q_3	1/2	1/3	— 1	— 2/3	0	— 1/3

As compared with quarks the antiquarks have opposite baryon, electric, and strange charges. The baryon number of the antiquark is —1/3, the electric charges are —2/3, +1/3, and +1/3, respectively, the strangeness of the third antiquark being +1. The spin and isotopic spin of antiquarks are the same as those of quarks.

Gell-Mann took the strange name of quarks from the first line of a song in the novel *Finnegan's Wake* by the well-known Irish poet and writer James Joyce. The song begins with the words "Three quarks...",

meaning the croaking of a frog. This name may be a hint at the dubious nature of the quarks, particles with fractional electric and baryon charges.

Hadrons formed from quarks must be distributed over unitary multiplets. The number of particles in multiplets is determined with the aid of the group theory. Mesons composed of a quark and an antiquark form, as in Sakata's model, a unitary singlet and a unitary octet:

$$3\times 3=1+8$$

Baryons are distributed over the following unitary multiplets:

$$3\times 3\times 3=27=1+8+8+10$$

Similar supermultiplets are obtained for antibaryons.

Let us consider in more detail formation of meson octets without resorting to the group theory. Table 22 indicates the electric and hypercharge of mesons which result from adding up the electric and hypercharges of a quark and an antiquark, respectively. All the nine mesons have zero spins, the spins of the quark and antiquark are oriented antiparallel when they are joined together. When a quark (q_1 or q_2) and an antiquark ($\tilde{q}_1$ or $\tilde{q}_2$) are added together their isotopic spins may be parallel (then the isotopic spin of the meson will be unity) or antiparallel (the isotopic spin of the meson will be zero). For the non-diagonal elements of the table ($\tilde{q}_1q_2$ and $\tilde{q}_2q_1$) the isotopic spin cannot be zero. The particle charge takes on values of $+1$ and -1, consequently the spin has three orientations of which two yield $+1$ and -1. Therefore only one value of the isotopic spin is possible, namely unity: the spin cannot be less than its component. The first two diagonal elements $\tilde{q}_1q_1$ and $\tilde{q}_2q_2$ may have an isotopic

TABLE 22

UNITARY OCTET AND SINGLET FOR MESONS WITH ZERO SPIN. (THE TABLE INCLUDES THE VALUES OF ELECTRIC CHARGE Q, HYPERCHARGE Y AND ISOTOPIC SPIN I $(Q,Y)_I$)

Q^q, Y / $Y^{\tilde{q}}$, Y	q_1 2/3, 1/3	q_2 −1/3, 1/3	q_3 −1/3, −2/3
$\tilde{q}_1$ − 2/3, − 1/3	$\tilde{q}_1q_1^*$ $(0,\ 0)_1$ $(0,\ 0)_0$	$\tilde{q}_1q_2=\pi^-$ $(-1,0)_1$	$\tilde{q}_1q_3=K^-$ $(-1,\ -1)_{1/2}$
$\tilde{q}_2$ 1/3, − 1/3	$\tilde{q}_2q_1=\pi^+$ $(1,\ 0)_1$	$\tilde{q}_2q_2^*$ $(0,\ 0)_1$ $(0,\ 0)_0$	$\tilde{q}_2q_3=K^0$ $(0,\ -1)_{1/2}$
$\tilde{q}_3$ 1/3, + 2/3	$\tilde{q}_3q_1=K^+$ $(1,\ 1)_{1/2}$	$\tilde{q}_3q_2=\tilde{K}^0$ $(0,\ 1)_{1/2}$	$\tilde{q}_3q_3$ $(0,\ 0)_0$

* Mixture of $\tilde{q}_1q_1$ and $\tilde{q}_2q_2$ with isospin 1 yields π^0-meson.

spin equal either to unity or to zero. When the isospin is unity, the corresponding particle belongs to an isotriplet; this is a π^0-meson. When the isospin is zero these elements are included in an isosinglet, a η^0-meson. The first and second diagonal elements $\tilde{q}_1q_1$ and $\tilde{q}_2q_2$ do not differ in any way, therefore we may consider that the π^0-meson is a mixture of two states with, a unit isospin:

$$\pi^0=\frac{1}{\sqrt{2}}\left(\tilde{q}_1q_1+\tilde{q}_2q_2\right)_{I=1}$$

and the η^0-meson is a mixture of the remaining diagonal states whose isospin is zero:

$$\eta^0=\frac{1}{\sqrt{6}}\left(\tilde{q}_1q_1-\tilde{q}_2q_2-\tilde{q}_3q_3\right)_{I=0}$$

TABLE 23

UNITARY OCTET AND SINGLET FOR MESONS WITH UNIT SPIN. (THE TABLE INCLUDES THE VALUES OF ELECTRIC CHARGE Q, HYPERCHARGE Y AND ISOTOPIC SPIN I)

Q^{q}, Y / $Q^{\tilde{q}}$, Y	q_1 2/3, 1/3	q_2 −1/3, 1/3	q_3 −1/3, −2/3
$\tilde{q}_1$ −2/3, −1/3	$\tilde{q}_1^{*} q_1$ $(0, 0)_{I=1}$ $(0, 0)_{I=0}$	$\tilde{q}_1 q_2 = \rho^-$ $(-1, 0)_{I=1}$	$\tilde{q}_1 q_3 = K^-$ $(-1, -1)_{I=1/2}$
$\tilde{q}_2$ 1/3, −1/3	$\tilde{q}_2 q_1 = \rho^+$ $(1, 0)_{I=1}$	$\tilde{q}_2^{*} q_2$ $(0, 0)_{I=1}$ $(0, 0)_{I=0}$	$\tilde{q}_2 q_3 = K^0$ $(0, -1)_{I=1/2}$
$\tilde{q}_3$ 1/3, 2/3	$\tilde{q}_3 q_1 = K^+$ $(1, 1)_{I=1/2}$	$\tilde{q}_3 q_2 = K^0$ $(0, 1)_{I=1/2}$	$\tilde{q}_3 q_3 = \varphi$? $(0, 0)_{I=0}$

* Mixture of $\tilde{q}_1 q_1$ and $\tilde{q}_2 q_2$ with isospin 1 yields ρ^0-meson.

The sum of all diagonal states with the plus sign (a symmetric combination) and a zero isospin yields a neutral particle, an isotopic singlet. It can be referred to a unitary singlet, which has not been discovered yet, but the search is going on.

The unitary octet depicted in Table 23 is obtained from a similar combination of quarks and antiquarks, but with spins oriented in the same direction. The spin of each of the particles obtained is unity.

A few meson resonances, whose mass is incidentally close to 1200 MeV (B-meson, A-meson, C-meson, etc.), cannot be fitted into any classification as yet.

Now we must find the possible supermultiplets for baryons and baryonic resonances, each of which is formed of three quarks. The method used above for de-

termining meson supermultiplets is inconvenient and self-contradictory, since in their determination electric charges were calculated, which characterize isotopic, but not unitary multiplets. To determine the number and type of isotopic multiplets in unitary multiplets we will now add up, not the electric and hypercharges of the quarks, but their isotopic spin and hypercharge. Therefore the first two quarks look like a single particle, an isodoublet. The second particle (the third quark) is an isosinglet.

Table 24 gives the possible values of the isospin

TABLE 24

POSSIBLE MESON ISOTOPIC MULTIPLETS

$\widetilde{I^q}, Y$ \ I^q, Y	q_1q_2 1/2, 1/3	q_3 0, —2/3
$\widetilde{q_1q_2}$ 1/2, —1/3	1, 0 0, 0	1/2, —1
$\widetilde{q_3}$ 0, +2/3	1/2, 1	0, 0

and hypercharge of isotopic multiplets formed from a quark isodoublet and a quark isosinglet combined with the corresponding antimultiplets. On the *Y*-*I*-plane (Table 25) we get a unitary mesic octet and unitary mesic singlet.

Adding up isospins and hypercharges of two quark isodoublets and isosinglets in a similar way, we obtain the intermediate values of isospins and hypercharges presented in Table 26. Summing them up with the isospins and hypercharges of two quark isomultiplets, as is done in Table 27, we obtain a set of isomultiplets

TABLE 25

MESIC UNITARY OCTET AND UNITARY SINGLET

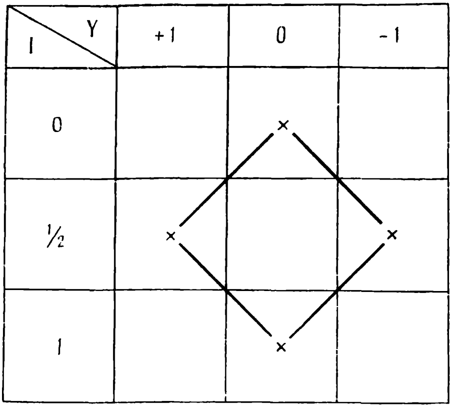


TABLE 26

INTERMEDIATE VALUES OF ISOTOPIC SPIN AND HYPERCHARGE

I^q, Y / $\widetilde{I^q}$, Y	$q_1 q_2$ 1/2, 1/3	q_3 0, —2/3
$q_1 q_2$ 1/2, 1/3	1, 2/3 0, 2/3	1/2, —1/3
q_3 0, —2/3	1/2, —1/3	0, —4/3

in which each particle consists of three quarks. Plotting the results on the Y-I-plane (Table 28), we clearly see two unitary octets, a decaplet, and a singlet.

The distribution of baryons and baryonic resonances

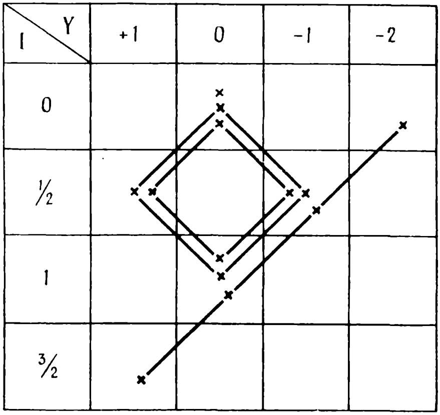
TABLE 27

VALUES OF ISOTOPIC SPIN AND HYPERCHARGE FOR BARYONS CONSISTING OF THREE QUARKS EACH

I^q, Y / $2q$, Y	q_1q_2 1/2, 1/3	q_3 0, —2/3
1, 2/3	3/2, 1	1, 0
0, 2/3	1/2, 1	0, 0
	1/2, 1	0, 0
1/2, —1/3	1, 0	1/2, —1
	0, 0	
1/2, —1/3	1, 0	1/2, —1
	0, 0	
0, —4/3	1/2, —1	0, —2

TABLE 28

DISTRIBUTION OF ISOMULTIPLETS OVER UNITARY MULTIPLETS FOR BARYONS CONSISTING OF QUARKS



over unitary multiplets (octets and a decaplet) has already been carried out in connection with the discussion of the Gell-Mann-Ne'eman model (see Tables 12-15). Here it is exactly the same, and we do not have to repeat it.

A few more words on parity. The proton, the neutron, and the lambda-hyperon in Sakata's model (as well as the fundamental baryons in the Gell-Mann-Ne'eman model, and also quarks) do not transform into each other as a result of strong interactions, in which parity is conserved. They transform into each other in weak interactions (the neutron disintegrates into a proton, an electron, and an antineutrino, and so on), but in weak interactions the parity is not conserved. Therefore the parity of these particles with respect to that of the other particles with which they enter into a strong interaction is essential. This property is associated with the property of the wave function. For a particle system the wave function is equal to the product of the wave functions of the particles comprising the system. It is known, for instance (and this has been proved convincingly), that the fermion and the antifermion have opposite parities. Therefore the wave function of a system consisting of a proton and an antiproton is antisymmetric, and the parity of the system is negative. A proton can be assigned any parity, either positive or negative, but on one condition: the parity of the antiproton should be opposite to it. The scientists have agreed to consider the parity of the proton, neutron, and lambda-hyperon to be positive, and that of the respective antiparticles, negative. From this it follows that the parity of all quarks (as well as the parity of all the eight fundamental baryons in the Gell-Mann-Ne'eman model) should be positive, and that of antiquarks, negative.

A particle obtained as a result of interaction of a

fundamental fermion with an antifermion (in any model) must have a negative parity by virtue of the law of conservation of parity. But this is true while the fermion and antifermion are in the *s*-state (the orbital moment of the initial system is zero). If the moment is non-zero, however, the parity of the initial system will be equal to the product of the parity of the particles and the orbital parity, which is equal to $(-1)^l$. Hence, the meson formed from the fermion and antifermion (according to any model) has a negative parity when the orbital moment of the initial system is zero, provided it is in the *s*-state. If the orbital moment is unity (the *p*-state), the parity of the meson obtained will be positive.

In all models, mesons and antimesons are obtained in the same way, i.e. from a fermion and an antifermion. Therefore the parity of the boson (all mesons are bosons) and the antiboson is the same.

The publication of the quark model aroused a keen interest. Scientists immediately began searching for them. But so far experiments have not produced any results. It has definitely been established that there are no particles with a fractional electric charge and a mass of less than 2 GeV. Maybe their mass will exceed 2 GeV, and they will be discovered in higher-energy experiments. Experimental discovery of quarks would be one of the greatest achievements of contemporary physics. But it is not improbable that quarks will not be found at all or it will be proved that they cannot exist, or this model will have to be abandoned when the theoretical results are compared with experiment. All the same, the quark model will always remain an extremely ingenious, logical, and harmonious formal scheme which has marked off the most interesting and arduous stages in the development of present-day physics.

Formula for Particle Masses in Unitary Multiplet

Unitary symmetry, as follows from very general considerations, should lead to regular relationships between the particle masses in a unitary multiplet. Indeed, all particles in a degenerated unitary multiplet should be undistinguishable and should possess an identical mass characterizing the supermultiplet as a whole. A moderately strong interaction, splitting a unitary multiplet into isotopic multiplets with different isospins and hypercharges, changes their masses. Such a change in mass should be associated with variations in the isospin and hypercharge. This is confirmed by experiment. In the unitary decaplet exhibited in Table 13 all the isomultiplets contained in the supermultiplet are equidistant with respect to the isospin and hypercharge. They have also proved approximately equidistant with respect to their mass. A certain regularity in mass variation when passing from one isomultiplet to another is noticeable also in the unitary octet portrayed in Table 12. When we speak of the mass of a particle in an isomultiplet, we imply complete degeneration with respect to the electric charge: we consider a particle whose mass is equal to the arithmetical mean of the masses of the particles contained in the isomultiplet. Thus, the mass of a nucleon is equal to the sum of the masses of proton and neutron divided by two (938.5 MeV). Instead of the three sigma-hyperons (positive, neutral, and negative with slightly different masses) we consider a sigma-hyperon with a mass of 1193.4 MeV, etc. For other unitary octets the absolute values of the masses will be different, of course, but the dependence on the isospin and hypercharge should remain unchanged.

Proceeding from general considerations and relying on his own intuition, the Japanese scientist S.Okuba obtained in 1962 a formula for particle masses in isomultiplets contained in a unitary multiplet:

$$m(IY) = m_0\left\{1 + aY + b\left[I(I+1) - \frac{1}{4}Y^2\right]\right\} \quad (20)$$

The constants m_0, a, and b appearing in the formula characterize the supermultiplet as a whole. Each supermultiplet must have its own values for these three constants, but we do not know them. They can, however, be eliminated and we can find the relationships between the masses of the particles contained in one and the same supermultiplet. Recalling school algebra, we will reproduce relationships between the particle masses in the unitary octet and the unitary decaplet.

For the octet, one can write four equations. Each of them is obtained by substituting the values of the isospin and hypercharge into equation (20) successively for all the isomultiplets contained in the unitary octet:

$$I = 0, \quad Y = 0 \qquad m_\Lambda = m_0$$

$$I = 1/2, \quad Y = +1, \qquad m_N = m_0\left(1 + a + \frac{1}{2}b\right)$$

$$I = 1/2, \quad Y = -1, \qquad m_\Xi = m_0\left(1 - a + \frac{1}{2}b\right)$$

$$I = 1, \quad Y = 0, \qquad m_\Sigma = m_0(1 + 2b)$$

Eliminating m_0, a, and b from the four equations, we obtain the relationships between the masses of the particles contained in the octet, which is valid for any octet because it does not contain the constants characteristic of the supermultiplet:

$$2(m_N + m_\Xi) = 3m_\Lambda + m_\Sigma \quad (21)$$

We wish to remind you once more that the masses appearing in equation (21) are the average masses of the particles comprising a given isomultiplet.

Equation (21) had been obtained by Gell-Mann also on the strength of unitary symmetry even before the Okuba relationship (20) was published. It holds good for the main octet to an accuracy of better than one per cent. Indeed,

$$3\times 1115+1193=2(939+1318.4)$$

or

$$4538\cong 4514$$

The deviation from a rigorous equality is

$$\frac{4538-4514}{4514}=0.006, \text{ or } 0.6\%$$

A unitary decaplet also contains four isomultiplets. Therefore we can compose four equations and eliminate the constants m_0, a, and b from them:

$$I=3/2,\ Y=+1, \qquad m_\Delta=m_0\left(1+a+\frac{7}{2}b\right)$$

$$I=1,\quad Y=0, \qquad m_\Sigma=m_0(1+2b)$$

$$I=1/2,\ Y=-1, \qquad m_\Xi=m_0\left(1-a+\frac{1}{2}b\right)$$

$$I=0,\quad Y=-2, \qquad m_\Omega=m_0(1-2a-b)$$

Subtracting one equation from another successively, we get three relations whose right-hand members are absolutely identical. Equating the left-hand members, we obtain the condition of equidistance of masses in a unitary decaplet:

$$m_\Delta-m_\Sigma=m_\Sigma-m_\Xi=m_\Xi-m_\Omega \tag{22}$$

As has been shown above, this condition is observed rather well.

The formula for masses in any meson octet differs somewhat from a similar formula in a baryon octet. For mesons, the constant a in Eq. (20) should be taken equal to zero, and the mass should be replaced everywhere by the square of the mass. Then relationship (20) yields, rather unjustifiably, the following relationship (previously obtained by Gell-Mann):

$$3m_0^2 + m_1^2 = 4m_{1/2}^2 \tag{23}$$

which holds good to an accuracy of about 3 per cent for the basic octet. The subscripts in relation (23) refer to the isotopic spin. Thus, the subscript 1 refers to an isotriplet (pi-meson), subscript 1/2 to an isodoublet (K-meson or K-resonance), subscript 0 to an isosinglet.

Equations (21)-(23) enable predicting the mass of the fourth particle (fourth isomultiplet), provided the masses of the three isomultiplets contained in the supermultiplet are known. This rule also helps in distributing the isomultiplets, discovered in experiment, over unitary multiplets. Thus, for instance, it helped establish a certain anomaly in the distribution of isomultiplets in a unitary meson octet with a spin and parity of 1^- (an octet of so-called vector mesons). According to Eq. (23) the isosinglet should have a mass of about 920 MeV. Two isosinglets with a suitable spin and parity—an omega-meson φ' (783,1^-) and a phi-meson φ (1019,1^-)—are eligible candidates for this place, but they cannot occupy it without any reservation. Their masses do not satisfy Eq. (23). It has been suggested that each of these mesons is a mixture of two mesons: a true isosinglet contained in a unitary octet and a unitary singlet which has the same spin and parity as the unitary octet. (That is

why they were mixed together.) As the result, two particles were formed with masses fitting neither a unitary octet, nor a unitary singlet.

Hyperfragments

A hyperfragment is an atomic nucleus in which one nucleon is replaced by a lambda-zero-hyperon. Hyperfragments were discovered in 1953 by Polish scientists M.Danysz and J.Pniewsky. Hyperfragments form on collison of a cosmic particle with a nucleus. The nucleus, receiving a great amount of energy, disintegrates; a so-called star appears, one of the fragments may contain a lambda-hyperon, this is a hypernucleus. Since a hypernucleus is a fragment it is called a hyperfragment.

Hyperfragments form not only on irradiation with cosmic particles. They are produced on accelerators when a substance is bombarded with protons and negative pi-mesons, and also as a result of capture of *K*-mesons by nuclei.

A lambda-zero-particle, having completed its lifetime, disintegrates within the nucleus. Therefore a hyperfragment is short-lived. If the hypernucleus is light (hydrogen, helium, lithium), it emits a negative pi-meson, as a rule, and sometimes one or several more particles, the balance forming a simple atomic nucleus. In light hypernuclei the lambda-particle disintegrates as if it were altogether outside the nucleus. This is only natural, because in a light nucleus the lambda, as well as the nucleons, is packed loosely.

In heavier hypernuclei the lambda-particle turns into a neutron, giving up its excess energy (about 175 MeV) and impulse to adjacent nucleons. This process is possible when the lambda is closely surrounded with

nucleons on all sides, more precisely when it is well mixed with them and packed tightly enough. Then the pi-meson emitted by it is captured by the nucleon and does not escape from the nucleus.

It is believed that the lambda-particle is bound with the nucleons in a hyperfragment by exchange and spin forces. It is binding energy with the nucleons that is lower than between the nucleons. As well as the nucleon binding energy, it increases with the mass of the hyperfragment (with an increase in mass number A).

TABLE 29

HYPERNUCLEI AND THEIR DISINTEGRATION CHANNELS

Hypernucleus	Disintegration channel	Binding energy of lambda-zero-particle in hypernucleus, MeV
$\Lambda\,H^3$	$^3He + \pi^-$	0.4 ± 0.3
	$^2H + p + \pi^-$	
	$p + p + n + \pi^-$	
$\Lambda\,H^4$	$^4He + \pi^-$	1.65 ± 0.4
	$^3He + n + \pi^-$	
	$^2H + n + p + \pi$	
$\Lambda\,He^4$	$^3He + p + \pi^-$	1.6 ± 0.4
	$^2H + p + p + \pi^-$	
	$^4H + p + \pi^-$	
$\Lambda\,He^5$	$^4He + p + \pi^-$	2.2 ± 0.4
$\Lambda\,Li^7$	$^7Be + \pi^-$	4.4 ± 0.9
	$^4He + {}^2H + p + \pi^-$	
$\Lambda\,Be^9$	$^8Be + p + \pi^-$	6.5 ± 0.6

Table 29 exhibits data on the disintegration channels and the binding energy of the lambda for certain best known hypernuclei. The existence of hyperhydrogen-4 and hyperhelium-5 stands out prominently in the table. There are no similar ordinary nuclei. To

obtain such heavy isotopes of hydrogen and helium we would have to add one neutron each to the nuclei of tritium and of ordinary helium. But the binding energy of neutrons is negative in these cases, and hydrogen-4 or helium-5 does not form. Why do hyperhydrogen-4 and hyperhelium-5 exist then? This seems to contradict the statement that the lambda is bound with the nucleons more weakly in a hypernucleus than the nucleons are with each other. But actually there is no contradiction. The point is that in hydrogen-3 and helium-4 the neutrons occupy the most advantageous (low) energy levels. According to the Pauli principle, new neutrons, being fermions and "individualists", can "settle" only on higher levels, where their binding energy is equal to zero in these cases. The Pauli principle does not prevent the lambda-hyperon from occupying the lowest and most advantageous energy level. There is only one lambda-particle in the hypernucleus, its levels are not filled; neutrons do not interfere with it, since it is a different type of particle, although it is electrically neutral like the neutron.

Table 29 does not list all the known hypernuclei. It can be extended up to hypercarbon-13, which is the heaviest hypernucleus known so far.

Incidentally, the important role of the spin in the lambda-nucleon bond within the hypernucleus is confirmed by the following observation. Hyperlithium-7 and hyperhelium-7 have the same number of nucleons, six, but the binding energy of the lambda in hyperlithium-7 is almost 2 MeV higher than that in hyperhelium-7. In both nuclei the lambda occupies the lower energy shell, which already accommodates four nucleons: two protons and two neutrons with pairwise antiparallel spins. Here, the nuclei do not differ from one another. But each nucleus has two more nucleons

one shell higher. In hyperlithium these are a proton and a neutron with parallel spins, in hyperhelium-7, two neutrons with antiparallel spins. The total spin of the nucleons in hyperlithium-7 is equal to unity, and in hyperhelium-7, to zero. Besides, these nuclei, of course, have a lambda spin, which is equal to 1/2. The fact that the binding energy of the lambda in hyperlithium-7 is higher than that in hyperhelium-7 is attributed to the existence of a spin in the nucleons comprising hyperlithium-7. The interaction of the total spin of the nucleons with that of the lambda increases the binding energy of the lambda. No such interaction can take place in hyperhelium-7 because the total spin of the nucleons is zero.

The existence of hypernuclei with a lambda alone and the absence of hypernuclei with other hyperons (sigma or xi) is explained by disintegration of the sigma and xi as a result of strong interactions on collision with nucleons. This disintegration does not contradict the law of conservation of strangeness. The lambda and sigma have the same strangeness, —1, and transformation of a sigma into a lambda does not affect the strangeness. The strangeness of the xi is equal to —2, but a xi-zero and a neutron taken together yield two lambdas, just as two lambdas are obtained when a minus-xi joins with a proton; the total strangeness of two lambdas is also —2.

The capture of a xi-hyperon by an ordinary nucleus may lead to the formation of a hypernucleus containing two lambdas. The reaction

$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5 \text{ MeV}$$

occurs inside a nucleus with one of the protons. Both lambdas remain in the nucleus.

A double hypernucleus was first discovered in 1963 by Danysz and coworkers on irradiation of a stack of

nuclear emulsions with K^--mesons of energy 1.5 GeV. The resulting Ξ^--hyperon penetrated a light nucleus (C, N or O) and formed a hypernucleus of boron B^{10}, which disintegrates according to the scheme

$$
\begin{array}{l}
{}_{\Lambda\Lambda}B^{10} \rightarrow {}_{\Lambda}Be^{9} + H^1 + \pi^- \\
\qquad\qquad \llcorner\!\!\longrightarrow 2He^4 + H^1 + \pi^-
\end{array}
$$

The energy of separation of the two lambdas from the nucleus is estimated at 19.0 ± 0.1 MeV. It is higher by $\Delta B_{\Lambda\Lambda} = 4.5 \pm 0.4$ MeV than the doubled binding energy of one lambda with the nucleus. This value, however, is not equal to the binding energy of the two lambdas. The fact is that the initial state of the nucleus emitting a single lambda in one case and two in the other, and the ultimate kinetic energy of the emitted particles may be different as well.

In 1966 D.Prowse discovered another case of a double hypernucleus. On irradiation of an emulsion stack with K^--mesons of energy 4.5 GeV the following reaction took place

$$
\begin{array}{l}
\Xi^- + C^{12} \rightarrow {}_{\Lambda\Lambda}He^6 + Li^7 \\
\qquad\qquad\quad \llcorner\!\!\longrightarrow \pi^- + p + {}_{\Lambda}He^5 \\
\qquad\qquad\qquad\qquad\qquad \llcorner\!\!\longrightarrow \pi^- + p + \alpha
\end{array}
$$

The binding energy of the two lambdas in the double hypernucleus of helium proved to be equal to 10.8 ± 0.5 MeV. The difference between this energy and

the doubled binding energy of the one lambda in the helium atom is equal to $\Delta B_{\Lambda\Lambda}=4.6\pm0.5$ MeV.

Rather complicated calculations with the use of the difference in the energies, $\Delta B_{\Lambda\Lambda}$, showed that there are forces of attraction between the two lambdas in the hypernucleus. Both of them are, naturally, on the lowest energy level and their spins are antiparallel according to the Pauli principle. These forces are slightly weaker than those operating between lambda and nucleon in the state with antiparallel spins (singlet state), but much stronger than those between lambda and nucleon with parallel spins (triplet state).

Investigation of hypernuclei enabled physicists to draw their conclusion about the spin and parity of the strange particles.

This ends our discussion of hypernuclei, the product of research in the second part of the twentieth century.

BASIC PHYSICAL MAGNITUDES IN THE SI SYSTEM

Magnitude	Symbol	SI Unit
Amplitude of oscillation	A	metre, m
Angular momentum	L	kilogram-square metre per second, $kg \cdot m^2/s$
Angular velocity	ω	radian per second, rad/s
Current intensity	I	ampere (A)
Density	ρ	kilogram per cubic metre, kg/m^3
Electric field force	E	volt per metre, V/m
Energy	E	joule, J
Force	F	newton, N
Frequency	f, ν	hertz, Hz
Gravitational acceleration	g	metre per square second, m/s^2
Half-life	t	second, s
Impulse of force	p, i	newton-second, $N \cdot s$
Kinetic energy	T	joule, J
Length	L, l	metre, m
Linear acceleration	a	metre per square second, m/s^2
Linear velocity	v	metre per second, m/s
Magnetic field force	H	ampere per metre, A/m
Magnetic moment	p_m	ampere-square metre, $A \cdot m^2$
Mass	m	kilogram, kg
Momentum	K, p	kilogram-metre per second, $kg \cdot m/s$
Potential difference	U	volt, V
Power	N	watt, W
Pressure	P	newton per square metre, N/m^2
Radiation dose	D	coulomb per kilogram, C/kg
Spectral radiation flux	Φ_λ	watt per metre, W/m
Time	t	second, s
Unit weight	γ	newton per cubic metre, N/m^3
Wavelength	λ	metre, m
Wave number	$\tilde{\nu}$	reciprocal metre, 1/m
Weight	P	newton, N
Work	A	joule, J

CONVERSION TABLE

1 electron-volt	$= 1.60210(2) \times 10^{-19}$ J
	$= 1.60210(2) \times 10^{-12}$ erg
	$= 8065.73(8)$ cm^{-1}
	$= 2.41804(2) \times 10^{-14}$ s^{-1}
1 eV per particle	$= 11604.9(5)$ °K
	$= 23061(1)$ cal · mol^{-1}
Unit mass ($C^{12} = 12$)	$= 931.478(5)$ MeV
Proton mass	$= 938.256(5)$ MeV
Neutron mass	$= 939.550(5)$ MeV
Electron mass	$= 511.006(2)$ eV
Gas constant	$= 8.31434 \times 10^{7}$ erg · mol^{-1} · deg^{-1}
	$= 0.082053$ l · atm · mol^{-1} · deg^{-1}
	$= 82.055$ cm^{3} · atm · mol^{-1} · deg^{-1}
	$= 1.9872$ cal · mol^{-1} · deg^{-1}
Standard volume of ideal gas	$= 22413.6$ cm^{3} · mol^{-1}
Thermodynamic calorie, cal	$= 4.184$ J
	$= 4.184 \times 10^{7}$ erg

TO THE READER

Mir Publishers would be grateful for your comments on the contents, translation and design of this book. We would also be pleased to receive any other suggestions you may wish to make.

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In these sketches, the late K. I. SHCHOLKIN, Corresponding Member of the USSR Academy of Sciences, gives a popular account of the structure of the atoms and atomic nuclei of matter and anti-matter, of nuclear forces and the structure of nucleons. His book tells about strong and weak interactions, parity and its non conservation, and vacuum polarization. Models of nuclei, nuclear fission, and fusion reactions are described, with basic information on elementary particles, and the latest technical advances of quantum physics (maser amplifiers, hydrogen-atom radiation, Mossbauer effect, etc.). There are also articles devoted to strange particles like K-mesons.

The book is in a clear and readable manner, and is intended for sixthformers and general non-technical readers who are interested in the latest developments in nuclear and atomic physics, i.e. the physics of the microworld.

The book has had three editions in Russian and has been translated into Spanish.